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Load Factors Obtained on Civil Airplanes in Acrobatic Maneuvers

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SUMMARY

Results of load factor measurements made by the Civil Aeronautics Administration on 38 small civil airplanes and the results of tests made by the N.A.C.A. for the Civil Aeronautics Administration, on five small civil airplanes, are presented. The maximum load factors measured in various maneuvers are summarized in Table 1. The tests made by the C.A.A. were for the purpose of determining the suitability of the airplanes involved for use in the acrobatic phases of the Civilian Pilot Training Program.

One particular feature of the tests by the C.A.A. was that the various maneuvers were conducted by first using a smooth technique and then by using a rough technique to simulate the action of an inexperienced student pilot. Following an analysis of the records thus obtained, the optimum entering airspeeds for the maneuvers on each particular airplane were determined for the purpose of placarding.

The effects of various factors such as entry speed, technique, etc., on the developed load factors are discussed.

TESTS

THE TESTS made by the C.A.A. were performed by members of the Flight Engineering and Factory Inspection Division. Although the purpose of these tests was to determine, from a general standpoint, the suitability of the airplanes for use in the advanced stages of the Civilian Pilot Training Program, only those points which pertain directly to load factors are within the scope of this paper.

The 38 airplanes used in the C.A.A. tests complied with the following Civilian Pilot Training requirements for secondary training aircraft:

Weight†—1301 to 4000 lbs.
Horsepower—120 to 225 hp.
Seating—Tandem
Cockpit—Open, or with sliding hatch
Control—Stick type

In view of the general similarity of the load factor results obtained on these airplanes, any further breakdown as to type, etc., is considered unnecessary.

The five airplanes used in the N.A.C.A. tests, with one exception, fell into the following classification:

Test weight—970 to 1060 lbs.
Horsepower—40 to 65 hp.

The pilots participating in the C.A.A. tests were requested to perform the various maneuvers throughout a range of entry speeds and then to finally determine the minimum entering airspeed at which each maneuver could be readily completed with a fair degree of skill.

TABLE 1

Maximum Load Factors in Various Maneuvers

Maneuver	n	Tests by
Positive Load Factors		
Snap Roll	5.2	C.A.A.
Vertical Reversement	4.0	C.A.A.
Loop	4.3	C.A.A.
Immelman	4.6	C.A.A.
Abrupt Pull-up	4.22	N.A.C.A.
Dive Pull-up	5.05	N.A.C.A.
Slow Roll	4.1	C.A.A.
Half Loop	4.7	C.A.A.
Spins(Recovery)	4.0	C.A.A.
Split S	4.0	C.A.A.
Vertical Roll	4.2	C.A.A.
Half Roll	4.5	C.A.A.
Negative Load Factors		
Inverted Stall	−1.5	C.A.A.
Inverted Pull-up	−2.0	C.A.A.
Slow Roll	−1.6	C.A.A.
Abrupt Push-down	−0.8	N.A.C.A.

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* Aircraft Engineering Division.

† Most airplanes in these tests weighed between 1760 and 2500 lbs.

TABLE 2

Load Factors Measured on 14 Airplanes (C.A.A. Tests)

ACCELERATION MEASUREMENTS IN POSITIVE MANEUVERS

Airplane No. —	1	2	3	4	5	6	7
Maneuver							
Snap Roll	3.0 to 3.6	**5.2***	3.0 to **4.0**	2.6 to **4.0**	2.6 to 3.5	2.8 to 3.8	3.3 to **3.9**
Vertical Reversement	3.0	3.6	2.7 to 3.7	3.4 to 3.6	2.2 to 3.2	2.6 to 3.5	2.5 to 3.4
Loop	2.8	3.2	2.8 to 3.5	2.4 to 3.2	2.7 to 3.2	2.4 to 3.9	2.8 to 3.2
Immelman	2.5 to 2.7	4.0	2.7 to 3.4	2.6 to 3.6	2.4 to 3.4	2.4 to 3.0	2.6 to 3.2
Slow Roll		2.8	2.2 to 3.2	1.8 to 2.3	2.6 to 3.3	2.5 to 3.0	2.3 to 2.7
Half Loop							
Spin (Recovery)	2.6	2.8	2.9 to **4.0**	2.6 to 2.7		2.8 to 3.2	2.0 to 3.6
Split S			2.4 to 3.4		3.0 to **3.8**	2.8 to **4.0**	3.1 to 3.8
Vertical Roll	**4.0**	4.2		3.0 to 3.1		3.8	
Half Roll				3.4 to 3.7			

* Full Snap Roll from Vertical Bank (Maximum acceleration for each airplane shown bold-face).

AIRPLANE _____ DATE OF TESTS _____ PILOT IN (FRONT) (REAR) SEAT
POWER _____ TESTS BY _____ NO. OF PASSENGERS _____
APPROX. WGT. DURING TESTS _____ ACCELEROMETER _____

(1) MANEUVER	(2) AIR CONDITION	(3) DIRECTION	(4) CONTROL USE	(5) TIAS IAS (CHECK ONE) ENTRY	RECOVERY	MAX. ACCELERATION POSITIVE	NEGATIVE	REMARKS	(7) MAXIMUM RECOMMENDED SPEED FOR MANEUVER
SNAP ROLLS*									
VERTICAL* REVERSEMENT									
LOOP*									
IMMELMAN*									
SLOW ROLL*									

FIG. 1. Condensed portion of maneuvering test data sheet.

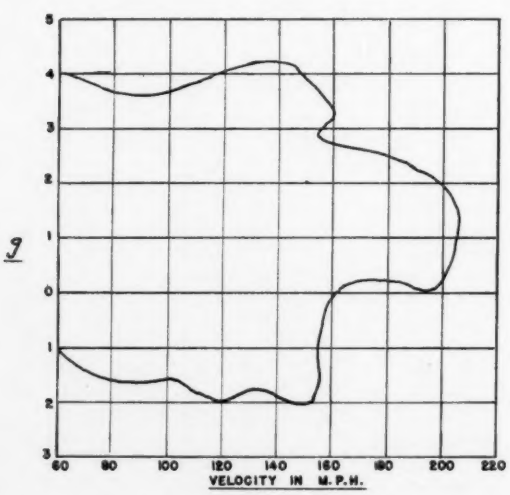


FIG. 2. Typical *V-g* record covering various maneuvers in a monoplane. (C.A.A. tests.)

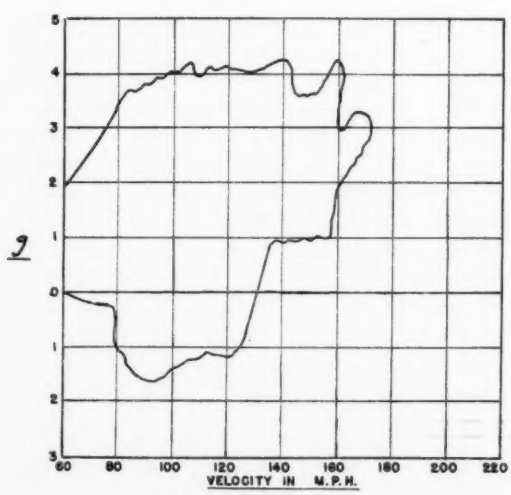


FIG. 3. Typical *V-g* record covering various maneuvers in a biplane. (C.A.A. tests.)

TABLE 2 (*Continued*)

Load Factors Measured on 14 Airplanes (C.A.A. Tests)

ACCELERATION MEASUREMENTS IN POSITIVE MANEUVERS

8	9	10	11	12	13	14	Range for Each Maneuver
3.4	**4.7**	**3.0**	**4.4**	2.5 to 3.0	3.2 to **3.5**	2.4 to **3.8**	2.4 to 5.2*
2.3	3.4	**3.0**	3.8	3.3	3.0 to 3.6	2.3	2.2 to 3.7
3.2	2.8 to 4.3	2.6	3.9	2.4	2.2 to 2.5	2.1	2.1 to 4.3
3.2	2.9 to 3.6	2.7	2.9	2.7	2.7 to 3.5	2.2	2.2 to 4.0
3.2	2.0 to 3.7	2.3	2.4	2.4	1.7 to 2.6	1.9	1.7 to 3.7
	4.2 to **4.7**						4.2 to 4.7
3.5	3.2 to 3.6	2.7	2.8	3.1 to 3.4		2.7	2.0 to 4.0
	3.0 to 3.3			3.0	2.0 to 2.5	2.3	2.0 to 4.0
							3.0 to 4.2
3.5	4.0 to 4.5	2.9	4.3				2.9 to 4.5

These pilots were informed that it was not considered advisable to exceed an acceleration of approximately 4*g* in these tests. Accelerations were measured by Kollsman and Pioneer visual accelerometers and also by means of N.A.C.A. *V-g* recorders, the latter instruments being used principally for checking purposes. In the N.A.C.A. tests, all acceleration measurements were made with *V-g* recorders.

It is estimated that the readings made with the visual recording accelerometers were, in general, within plus or minus 0.2*g* although the maximum error might have been of the order of plus or minus 0.4*g*. The accuracy of the accelerations obtained with *V-g* recorders is believed to be plus or minus 0.1*g*. Airspeed values were accurate within plus or minus 5 m.p.h.

The results of tests by the C.A.A. were, in general, recorded on a maneuvering test data sheet, a condensed portion of which is shown in Fig. 1.

RESULTS AND DISCUSSION

Load Factor Measurements

Typical *V-g* records covering various maneuvers performed in the C.A.A. tests are shown in Figs. 2 and 3, for a monoplane and biplane, respectively.

A *V-g* envelope covering various maneuvers of a light airplane in tests performed by the N.A.C.A. for the C.A.A. is shown in Fig. 4. In making these tests, the pilot was asked to perform any maneuver he desired, but of a severity he felt would be imposed by the average pilot. The airplane was equipped with a standard *V-g* recorder but did not have an air speed meter so that the pilot was forced to rely on his judgment for both the speed and severity of the maneuver. It will be noted from Fig. 4 that the pilot tended to limit himself to a constant maximum acceleration regardless of the airplane speed, for the positive range of accelerations. The high value of acceleration of 5.05g, however, is an exception, and is particularly interesting in that it indicates the magnitude of accelerations which may be developed at the discretion of a civil pilot if he is not informed of proper operating restrictions. In view of the limited nature of these tests, it appears quite likely that a somewhat higher limiting value might have been obtained if additional tests had been conducted or if additional pilots had been used.

Table 2 contains a summary of the load factors

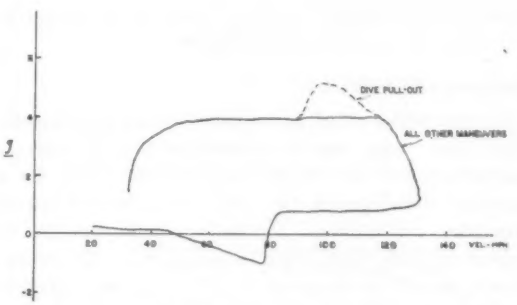


FIG. 4. *V-g* envelope covering maneuvers of a light airplane. (Tests conducted by the N.A.C.A. for the Civil Aeronautics Administration.)

Execute maneuvers with smooth and easy control pressures and at the lowest possible speed and acceleration

Maneuver	Recommended Speed of Entry
Immelman	130 m.p.h.
Loop	120 m.p.h.
Vertical Reversement	80 m.p.h.
Slow Roll	120 m.p.h.
Snap Roll*	85 m.p.h.
Max. Level Flight	115 m.p.h.
Never Exceed Speed	155 m.p.h.

* NOTE: In executing a snap roll care should be exercised not to pull back too abruptly on the stick. A fair snap roll can be executed without excessive accelerations by adhering to this procedure.

FIG. 5. Typical placard.

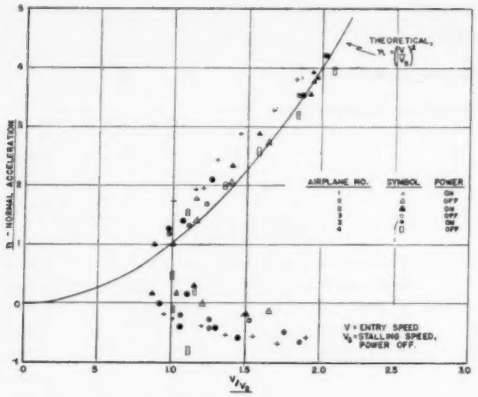


FIG. 6. Normal accelerations obtained on four light airplanes in abrupt pull-ups and push-downs, using full elevator deflection. (Tests conducted by the N.A.C.A. for the Civil Aeronautics Administration.)

measured in various "positive" maneuvers on fourteen out of the 38 airplanes tested by the C.A.A.

Operating Restrictions

As has been stated previously, one of the objects of the C.A.A. tests was to determine suitable operating restrictions on the various airplanes involved, for the purpose of informing the pilot as to proper entering airspeeds for various acrobatic maneuvers so that excessive loads would not be obtained. All airplanes which passed the required C.A.A. tests were therefore subsequently placarded in a manner similar to the typical placard shown in Fig. 5.

Abrupt Pull-ups and Push-downs

Fig. 6 shows the normal accelerations obtained on four light airplanes in abrupt pull-ups and push-downs using full elevator deflection. These tests were performed by the N.A.C.A. for the C.A.A. It is of particular interest to note that the load factors obtained in these abrupt pull-ups substantially exceed those given by the theoretical curve in the lower range of accelerations, but that they tend to scatter around the theoretical curve for accelerations in the neighborhood of $4g$, the latter value being about the upper limit of the "safe" load factor for most small commercial airplanes. The theoretical curve is based on the assumption that the airplane is pulled up from level flight to a C_L value corresponding to that at the power-off stalling speed, without any change in speed between the beginning of the pull-up and the time when the maximum load factor is obtained. The substantial increase in load factors over the theoretical values in the lower range of accelerations is discussed in previously published material.[1, 2] The increase is due to the increase in the maximum lift in the wing when the angle of attack is suddenly increased.

Although the lower values of g lie well above the theoretical curve, there should be no cause for alarm in regard to existing design specifications. It is common

TABLE 3

Acceleration Increment Due to "Rough" Technique (C.A.A. Tests)

Airplane	No. 3		No. 4		No. 5		No. 6		No. 7		No. 9		No. 13	
Maneuver	V*	Δn†	V	Δn	V	Δn	V	Δn	V	Δn	V	Δn	V	Δn
Snap Roll	80	.3	80	.4	70	.2	75	.3	80	.2	90	.8		
	85	.1	85	.6	80	.2			90	.2	100	.9		
			90	.5	85	.6								
			95	.1										
			100	.4										
Vertical Reversement	60	.1	85	.2	60	.2			60	.2				
	70	.1			70	.2			70	.2				
	80	.2			80	.2			80	.2				
Loop	90	.1	120	.6	110	.4	110	.3	110	.3	100	.8		
	100	.3	130	.8			120	.5			110	.3		
	110	.4												
	120	.1												
Immelman	100	.2	130	.8	110	.3	130	.3	110	.2	100	.5	150	.8
	110	.4	140	.8	120	.7			120	.3	110	.4		
	120	.3												
Slow Roll	120	.8	100	.5	100	.3	110	.1	80	.2	80	.5	120	.1
									100	.2	90	.0		
									120	.1				
Split S	70	.1			60	.1	80	.1	70	.7	90	.4		
	80	.2			70	.3	90	.2	80	.4				

* V = Indicated entry speed.

† Δn = Increase of "rough technique" load factor over "smooth technique" load factor.

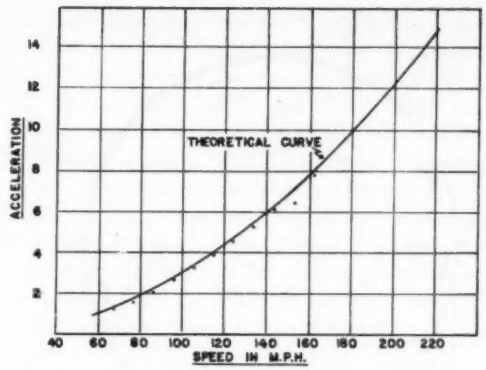


FIG. 7. Load factors on PW-7 (Fokker) resulting from sharp pull-outs.

in these specifications to design the structure for a point on the *V-g* envelope corresponding to the position of the maximum expected maneuvering factor on the "theoretical" curve. Since the actual *limit* strength line for the front spar (or its equivalent) will either pass through or will lie above this point, and will have a rather flat slope upward toward the right, it is obvious that the actual strength of the airplane will be adequate to take care of the dynamic overlift conditions which occur in the lower range of accelerations.

A comparison between Figs. 7 and 6 is interesting. Fig. 7 shows the load factors obtained in sharp pull-outs on a PW-7 (Fokker) pursuit airplane, and covers a higher range of *g* values than Fig. 6. In Fig. 7 it will be noted that all of the test points, with the exception of the point at 153 m.p.h., lie on a smooth curve which falls below the theoretical curve by approximately 3.5 per cent.

Effects of "Rough" Technique

The increase in accelerations in the tests conducted with "rough" technique over those conducted with "smooth" technique is shown in Table 3. It will be noted that the increase in acceleration due to the rough handling of controls varied between approximately 0*g* and 0.9*g*. The least increase in acceleration appears to occur in connection with the vertical reversements where the maximum increment was 0.2*g*.

It was anticipated that the smallest increments in acceleration between "smooth" and "rough" technique would be found in the case of relatively slow speed maneuvers such as vertical reversements and snap rolls. Whereas this would appear to be true in the case of vertical reversements, which showed a maximum increment of 0.2*g*, it appeared that the increments experienced in snap rolls ran as high as those which were developed in "high speed" maneuvers such as loops and Immelmans.

Combined Effects of Entry Speed and Technique

Further information on the effects of handling technique is given in Fig. 8, which contains three frequency

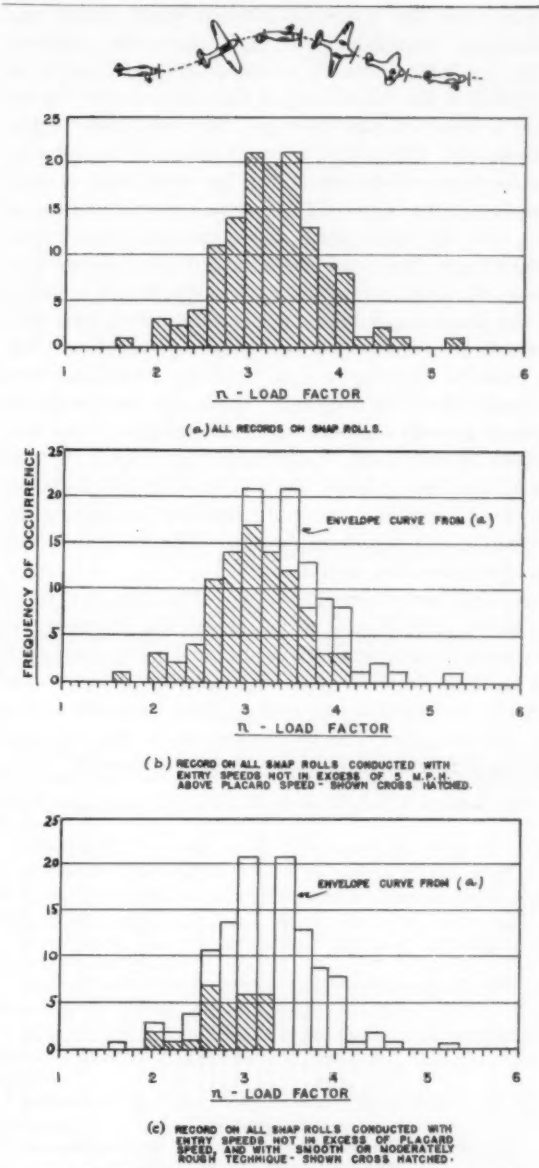

n - LOAD FACTOR
(a) ALL RECORDS ON SNAP ROLLS.
FREQUENCY OF OCCURRENCE
ENVELOPE CURVE FROM (a.)
n - LOAD FACTOR
(b) RECORD ON ALL SNAP ROLLS CONDUCTED WITH ENTRY SPEEDS NOT IN EXCESS OF 5 M.P.H. ABOVE PLACARD SPEED - SHOWN CROSS HATCHED.
ENVELOPE CURVE FROM (a.)
n - LOAD FACTOR
(c) RECORD ON ALL SNAP ROLLS CONDUCTED WITH ENTRY SPEEDS NOT IN EXCESS OF PLACARD SPEED, AND WITH SMOOTH OR MODERATELY ROUGH TECHNIQUE - SHOWN CROSS HATCHED.

FIG. 8. Frequency curves showing effect of entry speed and technique on load factors obtained in snap rolls. (C.A.A. tests.)

curves showing the effects of entry speed and technique on load factors obtained in snap rolls. This covers records on 38 airplanes tested by the C.A.A. Fig. 8(a) shows the frequency distribution of the *g* values obtained in all C.A.A. tests in which snap rolls were performed. It will be noted that an acceleration of about 3.3*g* is most probable, that an acceleration of 4*g* was experienced several times, that there were a few scattered accelerations between 4.0 and 5.0*g* and that a maximum acceleration of 5.2*g* was experienced on one occasion. Fig. 8(c) (cross-hatched position) gives a frequency curve for snap roll load factors which were obtained with entry speeds which were not in excess of 5

m.p.h. over the snap roll placard speed which was eventually established for each particular airplane. This, in effect, shows the accelerations which might be obtained if the pilots obeyed the placard entry speed with a plus 5 m.p.h. tolerance, but were more or less unrestricted with regard to rough usage of the controls. Under these conditions it will be noted that a large number of the higher values of acceleration shown on Fig. 8(a) are eliminated, the maximum value of acceleration in these cases being about 4.0. Figure 8(b) shows the load factors obtained at speeds not in excess of the placard speeds eventually established, and with smooth or moderately rough handling technique (that is, records covering rough handling technique were excluded from this diagram). Although there were not enough records obtained to prove anything very conclusive on this point, it is evident that complying with the placard speed restriction and avoiding rough control use would appear to be quite effective in reducing the probability of high load factors. The maximum load factors in this case were about 3.3.

As a matter of comparison with Fig. 8(a), it is interesting to note Fig. 9 which shows the frequency of occurrence of accelerations as obtained in 340 maneuvers on fourteen different types of English airplanes.[4] The highest acceleration obtained in these tests was 4.8*g* in an upward roll. The conclusions from this reference are quoted below as a matter of general interest.

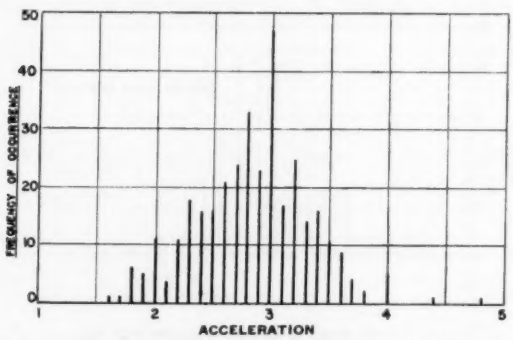
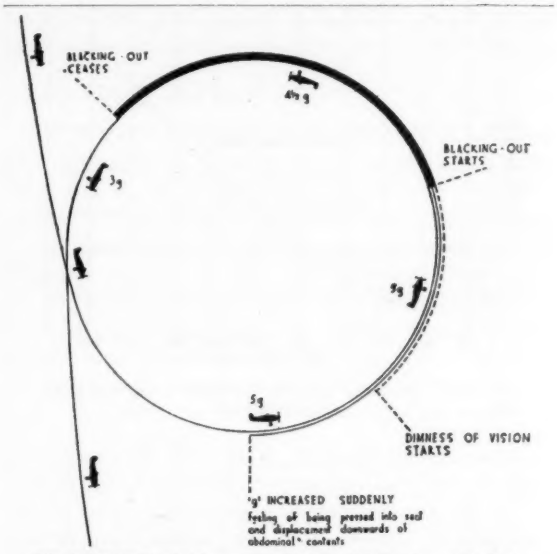


FIG. 9. Frequency of occurrence of accelerations as measured on English aircraft.

"For correctly performed maneuvers the average maximum acceleration is of the order of 3g and the minimum of the order of 0g. There is evidence to show that for indifferently performed maneuvers considerably higher values are likely to be obtained."

Physiological Factors

It might be well now to review the maximum positive load factors in various maneuvers as listed in Table 1. It will be noted that these factors range from 4.0 to 5.2 for the various maneuvers. It is quite likely that the main factors limiting these acceleration values was the black-out, or, perhaps more properly, an approach to the black-out. This is excellently illustrated in Fig. 10 which was taken from *The Aeroplane*.[5] It is well



THE BLACK-OUT.—This diagram, reproduced from the "Proceedings of the Royal Society of Medicine," illustrates how black-out is caused by continuous application of "g." If the "g" is applied in the opposite direction a phenomenon known as "redding-out" occurs caused by the concentration of blood in the head.

FIG. 10. (See *The Aeroplane*, March 28, 1941.)

known that the average pilot will tend to black-out if an acceleration greater than about 4*g* is experienced for a few seconds. On the other hand, it is well known that higher values of acceleration can be experienced by the average pilot if they are applied over a shorter period of time. Of course, the exact values of acceleration required for a black-out depend to a large extent on the physical condition of the pilot as well as many other factors, and it is reasonable to expect that a military pilot who has been acclimated to high load factors could withstand considerably higher values than the average civil pilot. In consideration of these facts it is believed that the range of maximum load factors previously mentioned was governed to a large extent by the feeling of discomfort experienced by the pilots at relatively high load factors.

It is fortunate that the results of a black-out or an approach thereto give us at least a somewhat definite limitation to the values of acceleration which the average civil pilot is willing to experience. However, this can only be of value toward limiting the values of accelerations if the pilot will avoid an extremely abrupt use of the controls. If, on the other hand, the civil pilot ignores this precaution and engages in extremely abrupt maneuvers at high speeds, it is quite probable that he can subject the airplane to load factors of the order of 6 or 7 and that he will receive the physiological sensation associated with a black-out too late for it to act as a deterrent against obtaining such load factors.

Maneuvering Speed

With reference to Fig. 6 it will be noted that there is a theoretical limit, as a function of speed, to the load

factors which can be obtained in abrupt pull-ups (or pull-outs). This is fortunate in that it permits the setting of a placard speed below which abrupt pull-outs can be made without the danger of exceeding the safe load factor for the airplane involved. (See the discussion of "maneuvering speeds" given in reference 6.) Thus, the most important rule for the civil pilot with regard to avoiding excessive load factors is as follows: "*Don't make abrupt pull-ups (pull-outs) at speeds above the safe maneuvering speed for your airplane.*" (Steps are now being taken to establish the safe maneuvering speed for all civil airplanes in current use.)

Load Factors in Spins

The previous reference[6] also shows the theoretical load factors which are obtained in steady turns with various angles of bank. It may be of interest to note that there are definite theoretical values of load factors which are obtained in steady spins, as is shown in Fig. 11. It should be noted that the load factor given for spins in Table 1 refers to the load factors obtained during the recovery from the dive following the spin.

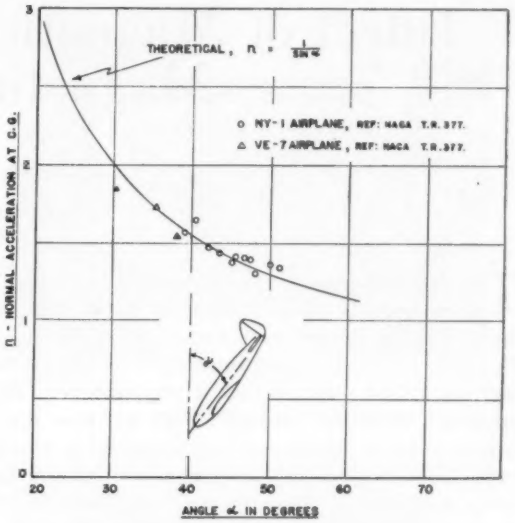


FIG. 11. Load factors in spins.

CONCLUSIONS

The load factor measurements reported herein are regarded as being a sufficient basis for a revision to the present maneuvering load factor requirements for small civil airplanes and also a basis for the possible establishment of an acrobatic category. It should be noted that the tests made by the C.A.A. were under conditions where the pilot was instructed not to exceed approximately 4.0*g*. This fact should be carefully considered if an acrobatic category is set up for civil airplanes and it would be well to make some allowance over the maximum values of accelerations recorded herein in order to obtain limit maneuvering factors which would be suitable for extensive acrobatic maneuvers by semi-skilled student pilots. This matter is being actively studied now by the C.A.A. along with a parallel study of the maintenance records of airplanes which have been used in the acrobatic stages of the Civilian Pilot Training Program.

REFERENCES

[1] Silverstein, A., Katzoff, S., and Hootman, J. A., *Comparative Flight and Full-scale Wind-tunnel Measurements of the Maximum Lift of an Airplane*, N.A.C.A. Technical Report No. 618, October 26, 1927.

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Effect of Magnetic Field Distribution in Magnetic Inspection

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THE PRESENT WIDE USE of magnetic testing for flaws in parts made of magnetic metals has given rise to many problems because of the complex shape of the parts. In many instances regions of intense magnetic saturation occur in such a way that very slight variations in surface structure such as those due to forging will give very strong indications while adjacent regions not magnetically saturated are substantially free of indications. It is the purpose of this paper to describe an investigation of this phenomenon in an eccentrically cylindrical crank pin section of an aircraft engine crankshaft.

Fig. 1a shows the shape of the specimen. Figs. 1b, 1c and 1d show the results obtained for different magnetizing currents applied in accordance with the common practice of passing current through a conductor located inside the cylindrical part. It was noted that there was a rather critical value of current of about 600 amps. above which marked indications appeared on the thin section outer surface. However, the remaining outer surface was found to be free of such indications even at the highest magnetizing currents. Figs. 2a and 2b show the result of testing a similar crank pin which was made concentric by internal boring. Note that a much higher current was then necessary to produce indications because more metal had to be saturated. Also note that flow lines were indicated on both thin and originally thick sections. In all of these photographs the forging flash was located in the region of the heavy indications. Hence it was at first thought that the flash was solely responsible. However, Figs. 3a and 3b show a crank pin in which the flash as indicated

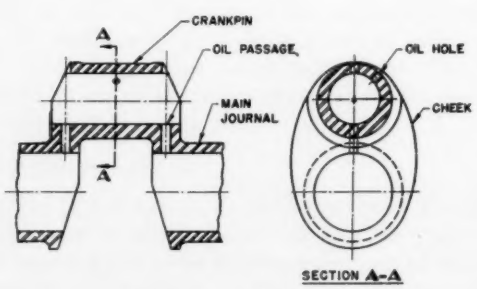

FIG. 1a. Test specimen.

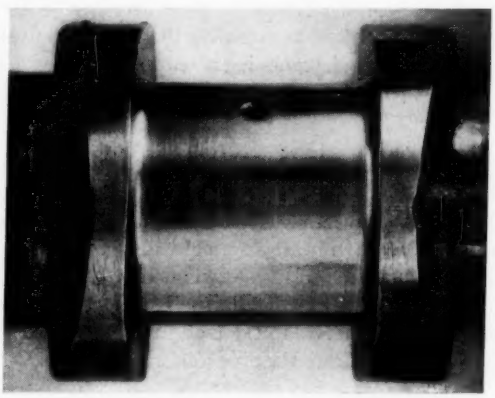

FIG. 1b. 800 amps. Continuous method.

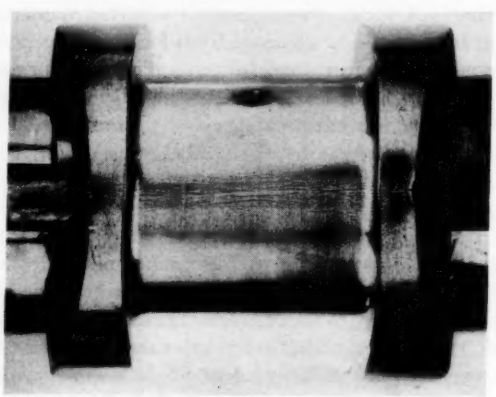

FIG. 1c. 3000 amps. Continuous method.

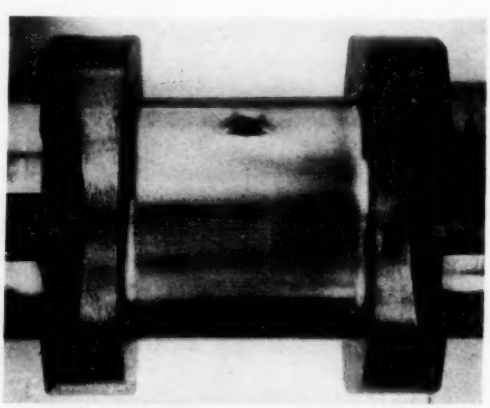

FIG. 1d. 6000 amps. Continuous method.

Presented at the Materials session, Tenth Annual Meeting, I.Ae.S., New York, January 29, 1942.

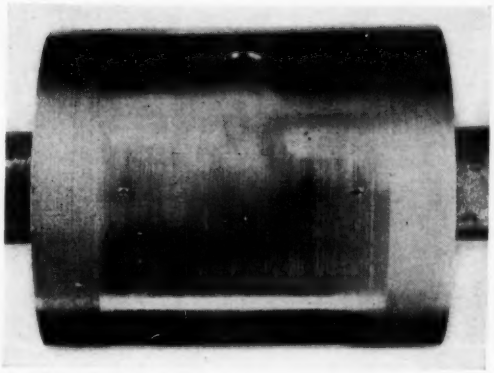

FIG. 2a. Thin section of concentrically bored pin. 6000 amps. Continuous method.

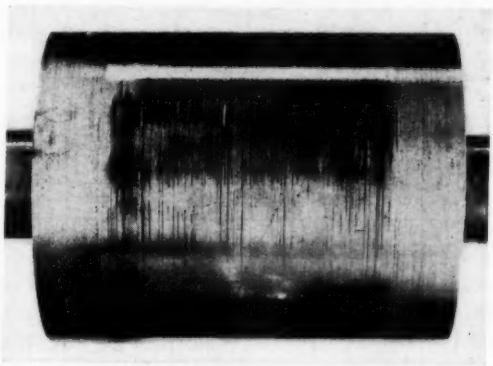

FIG. 2b. Thick section of concentrically bored pin. 6000 amps. Continuous method.

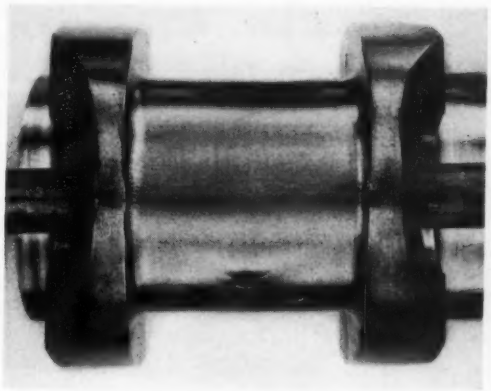

FIG. 3a. 3800 amps. Continuous method.

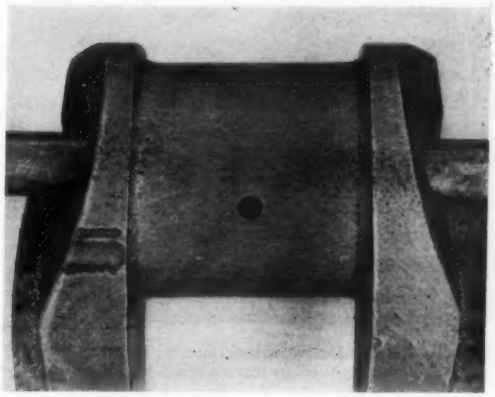

FIG. 3b. Same pin as in Fig. 3a but with surface etched to show the flash location.

by etching was actually about 15° away from the region of the heaviest indications which was at the thin section. It will be noted that the indication pattern in every case was definitely that due to forging flow.

FLUX MEASUREMENTS

In order to investigate the nature of the foregoing phenomena it was decided to make actual measurements of the magnetic flux through the thick and thin sections of the specimen. Two search coils of three turns each were wound closely to the metal as shown in Figs. 4a and 4b. In the case of the thick section coil, the wires are passed through the oil passages in the crank cheeks. When magnetic flux is passed through a coil of this type, its magnitude is the time-integral of the induced voltage per turn during the time interval over which the flux is established.[1] Fig. 5 illustrates the method which was used in order to measure the flux in the fraction of a second during which it is established and removed by the machine. The output of each search coil was impressed on an integrating amplifier of the type shown. The integrating feature is the resistor and capacitor series combination in the output circuit of the first amplifier tube. The output of the amplifier was impressed on the galvanometer element of an oscillograph so that the flux-time variation from instant to instant was recorded on photographic film.

The amplitude of the oscillogram as illustrated by (A) in Fig. 5 is related to the flux by the following expression:

$$A = (K/a)\int_1^2 E dt = (K/a)N\phi \qquad (1)$$

where

- A is the initial deflection of the galvanometer as shown at (A) in Fig. 5.
- t is time determined by the rate of film travel.
- E is the output voltage of the search coil.
- N is the number of turns of the search coil.
- ϕ is the flux through the coil.
- a is the attenuation ratio of the amplifier input control.
- K is the calibration constant of the system.

In order to obtain the calibration constant, a 60-cycle voltage from the power mains was impressed upon the amplifier and the time-integral of this voltage was recorded by the oscillograph. The double amplitude of this record is related to the input voltmeter reading as follows:

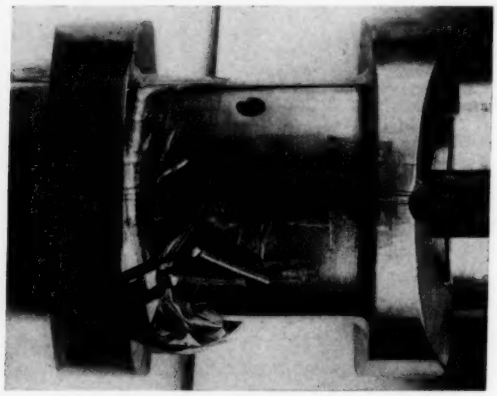

FIG. 4a. Method of attaching search coil.

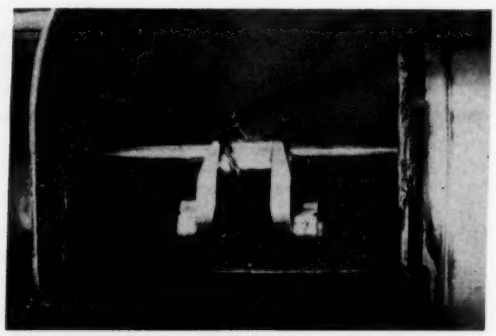

FIG. 4b. General view of specimen with search coils as mounted in testing machine.

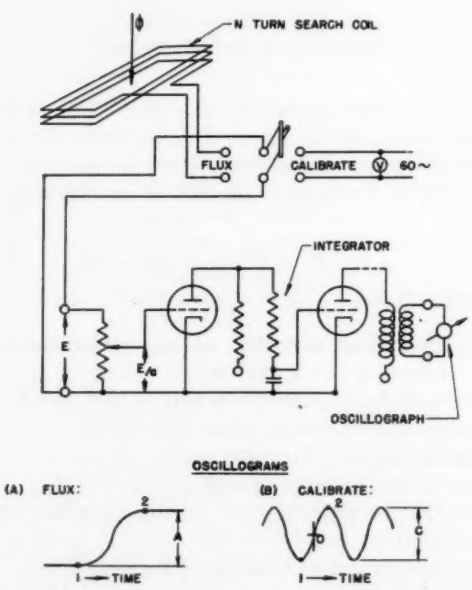

FIG. 5. Method of obtaining flux from search coil voltage.

$$C = (K/a_c)\int_1^2 2^{1/2} V \cos(2\pi\, 60t) \times dt = (2^{3/2}/377)\,(V/a_c)K \quad (2)$$

C is the amplitude of trace as shown in (B) of Fig. 5.

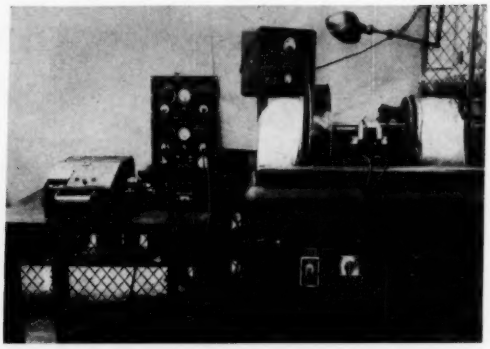

FIG. 6. General view of flux measuring equipment.

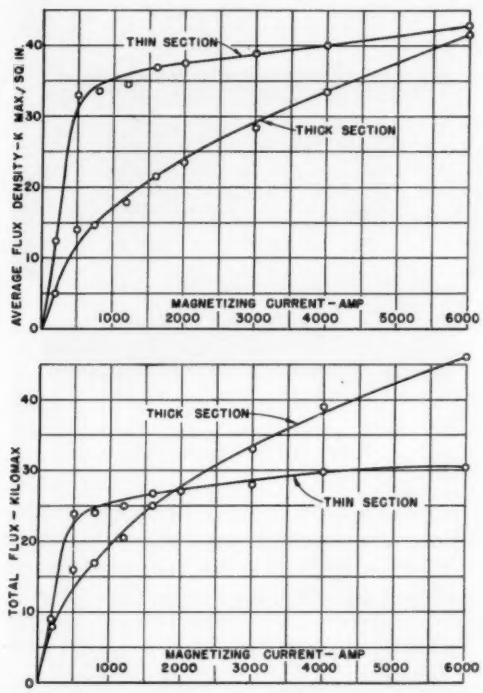

FIG. 7. Graphs of flux and flux density in thick and thin section search coils.

V is the reading of the rms. voltmeter connected across the amplifier input.

a_c is the attenuation ratio used during calibration.

If the value of K from Eq. (2) is substituted in Eq. (1) and the result solved for flux, the following relation for the flux is obtained.

$$\phi = (2^{3/2}/377)\,(a/a_c)(V/N)(A/C)10^5 \text{ Kilomaxwells} \quad (3)$$

Fig. 6 shows how the test specimen with the search coils on the thin and thick sections was mounted in the magnetic testing machine. Two separate integrating amplifiers are shown. One was connected to each search coil. The outputs were connected to two separate elements in the oscillograph which appears at the extreme left. In this way, simultaneous records

were taken of the time-integral of the voltage or the magnetic flux in each search coil.

Fig. 7 gives the results of these measurements of flux plotted against test conductor current. The current is also numerically equivalent to the magnetomotive force since the conductor bar constitutes one turn linked with the crank pin. It will be noted that, in the case of the total flux curves, the thin section flux rises rapidly and then bends over sharply indicating that magnetic saturation has been reached. The thick section flux curve rises more slowly without indicating saturation by a rapid change in slope. Above 2000 amps. magnetizing current, the thick section flux exceeds that of the thin section, while below this value the thin section flux is greater. This behavior may be explained as follows: The thin section becomes saturated at about 500 amps. because the flux density in that section then attains the saturation value for the material. Below 500 amps., saturation does not exist in the thin section so little flux is shunted around it through the air. Moreover, some of the thin section flux does not pass through the thick section search coil which is wound through the oil holes. Instead, it circulates through that portion of the cheeks which is not linked with the coil. Above 500 amps. the thin section is highly saturated. This saturation results in a high magnetic potential difference across the thin section and a local decrease in permeability of the metal. Consequently, the flux due to the additional current above 500 amps. leaks to a great extent through the air and hence does not pass through the thin section search coil. This leakage increases for greater magnetizing currents until the thick section flux exceeds the thin at 2000 amps. The thick section flux continues to increase quite rapidly without saturation up to the maximum current limit of the machine of 6000 amps.

Curves of average flux density in the thin and thick sections are also given in Fig. 7. They are plotted against magnetizing current. The general shape of the curves is similar to that of the total flux curves since the flux density values are obtained by dividing the flux measured by each coil by the cross sectional area enclosed by that coil. It will be noted that the thick section flux density is everywhere less than that of the thin even at 6000 amps. This fact indicates that the saturated thin section acts as a sort of magnetic dam and prevents the flux in the thick section from increasing to a value where flow line indications can be produced on its outer surface.

Magnetic Field Distribution Analysis

In order to understand the preceding phenomena more completely, it is helpful to consider the physical nature of the magnetic fields involved. The first analysis to be presented has as its purpose the investigation of the configuration of the field within the crank pin, taking advantage of all possible simplifying assumptions. In Fig. 8 the cross-section of the pin is shown with the conductor in position and carrying the magnetizing current. The direction of current flow is taken as into the plane of the page. The amount of current is assumed low so that saturation does not occur anywhere. It will be assumed that the material of the crankshaft has a permeability which is extremely high as compared to the permeability of the surrounding air. Under this condition, the inner and outer surfaces may be considered as magnetic flux paths. The direction of flow is indicated by the arrows. It is assumed that the field is two-dimensional. The magnetic flux field existing in the interior, which is assumed to be composed of homogeneous and continuous material, will be represented as shown by the solid accentric circles marked with directional arrows. The lines of equal magnetic potential or equipotential lines are the dotted circular arcs. These arcs are drawn orthogonal to the flux lines. The flux and potential lines tend toward rectangles when an infinite number are drawn to map the field. The ratio of the flux side of one of these element rectangles to the length of its potential side is the permeability of the material to a magnetic field. For purposes of illustration in the figure the relative permeability was taken as about 6 referred to that of a vacuum.

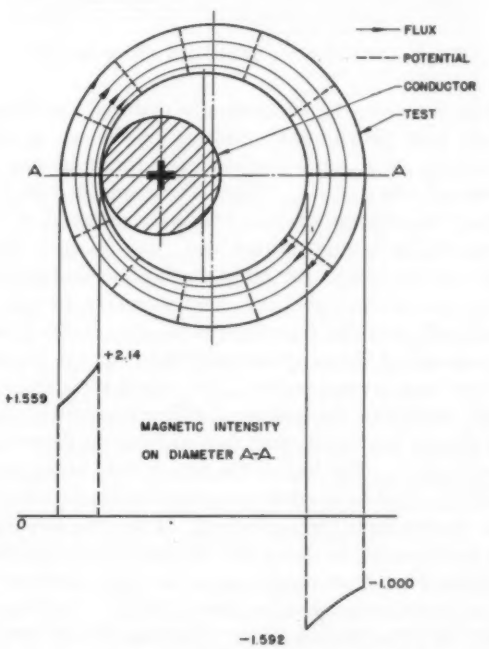

Fig. 8. Cross-section map of field in crank pin.

Reference to Fig. 8 shows how the outer surface flux density is greater for the thin side than for that in the thick side. Fig. 8 also gives in graphical form the variation in magnetic intensity (permeability times flux density) across the diameter of symmetry. This is a computed result derived from the equation of the field. It is quite apparent from Fig. 8 that the thin side outer

surface is likely to be more sensitive to flaw and flow line indications since the field intensity there is nearly 60 per cent greater.

The position of the conductor will not materially alter the field distribution in the metal except for conditions of high saturation. The reason is that the metal is many times as good a conductor, when not saturated, as the surrounding air. However, there will be a limited local field distortion in the metal near the point of contact between the conductor and the crank pin surface.

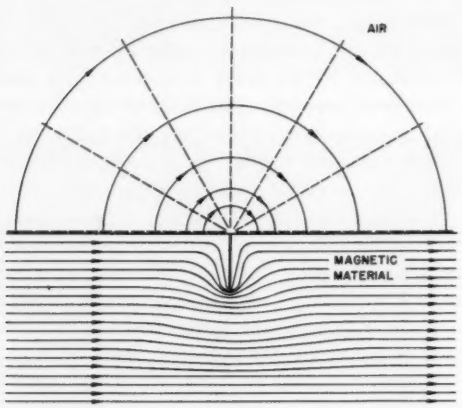

FIG. 9. Field in the neighborhood of a surface flaw.

Fig. 9 shows the theoretically deduced two-dimensional field distribution resulting in the air in close proximity to a small surface irregularity having the nature of a thin crack. This field is computed with the aid of the assumption that the body material of high permeability is unsaturated and that, in close proximity to the crack, the body surface is equipotential. It is evident that the high field intensity around the crack will cause the deposition there of a relatively large percentage of the magnetic particles from the liquid in which they are suspended. The metal surfaces to the right and left of the flaw are at different potentials since the flux in the metal must flow around the flaw at high flux density. The higher the flux density in the metal, the higher will be the difference between these potentials and the stronger the indication. The close spacing of the flux lines in the metal and the lack of appearance of equipotential lines results from the high permeability of the metal as compared to that of the air. Only a relatively few flux lines leak out from the metal into the surrounding air. Virtually a 90° refraction occurs for the portion of the field which leaks from just inside the metal out into the surrounding air. This refraction takes place very close to the boundary surface and is not shown. The effect of magnetic saturation on the fields of Figs. 8 and 9 would be to cause a point-to-point variation in rectangle side ratios on permeability in the saturated regions. The complexity of the mathematical analysis is greatly increased, but with the exception of previously described "damming" and leakage effects saturation does not materially affect the indication patterns.

CONCLUSION

In the inspection of the crank pin by the method just described it is possible that serious flaws might be overlooked if they should occur in the thick portion. It is hence desirable to equalize the field distribution throughout the pin. One possibility suggests itself at once. The conductor might be moved to the center of the interior. However, it should be noted that this change can never improve the distribution over that of Fig. 8 since that field was derived from the assumption that the position of the conductor is of no importance as long as it is contained within the inner cylinder.

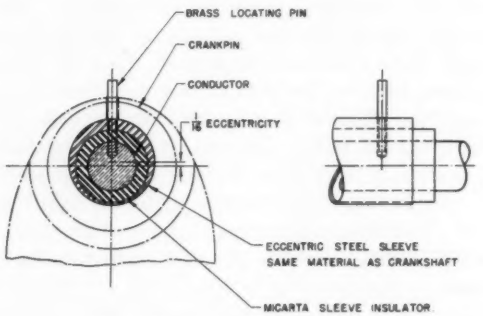

FIG. 10. Equalizing fixture for crank pin.

A more effective method which has been proposed is illustrated in Fig. 10 in which the section is made concentric by the insertion inside of the pin of a suitable eccentric sleeve of the same material as the crankshaft. As the structure is now practically symmetrical, the field will be uniform throughout the volume and surface flaws of a given magnitude will be visible to the same degree on any part of the periphery. The lack of symmetry will be due to the fact that some minute air gap will exist between the eccentric sleeve and the crank pin inner surface.

It is apparent that in magnetic inspection the geometry of the fields set up within irregularly shaped specimens has an important bearing on the character of the indications obtained and also on the interpretation of these indications. The author will feel well repaid for his efforts in the preparation of this paper if it leads to improved results in this type of inspection through similar field analyses.

REFERENCES

[1] Hazeltine, L. A., *Electrical Engineering*, page 106, Macmillan, New York, 1924.

[2] Jeans, J. H., *Mathematical Theory of Electricity and Magnetism*, Cambridge University Press, Cambridge, 1925.

[3] Müller, E. A. W., *Influence of Field Distribution on Flaw Distinctness in Magnetic Powder Testing*, V.D.I., Vol. 84, pages 472–476, 1940.

Flash Butt Welding of Chrome-Molybdenum Steel

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Introduction

Flash butt welding of steel has been an established industrial process for many years. The automobile industry, in particular, has used this process to take advantage of the low cost, high rate of production and excellent physical properties of the weld.

Application of this process to chrome-molybdenum steels has been very limited, especially in the aircraft industry. Limiting factors for aircraft application have been a lack of production volume, necessary equipment and experience. A natural tendency on the part of aircraft designers has been to exercise caution in the use of processes deviating from long established practices. In recent years, with the advent of large contracts, it has become advisable to investigate the possibilities of this process in structural design.

This article will give a brief outline of the many variables involved in the process as well as part and die design. Only in recent years has any effort been made to determine the individual effect of the various factors involved with respect to aircraft steels. It should be remembered that this process as applied to chrome-molybdenum steel is in the development stage and many of the procedures used at the present time may be discarded as a result of further research and additional experience.

Flash Welding Process

ALL RESISTANCE WELDING PROCESSES may be likened in basic principle to the old method used by blacksmiths. Pieces to be joined are first brought to fusion temperature in a forge, after which they are hammered together to produce a weld. In resistance welding the heat is generated electrically and the pressure produced mechanically.

Flash butt welding differs from projection and spot welding in the method used to generate the welding heat. This process must not be confused with the push type of butt welding in which parts are held together under pressure, current applied and heat generated, in accordance with Joule's Law of I^2RT. When parts reach fusion temperature, pressure sufficient to cause an upset weld is applied. In flash butt welding, the heat is not generated under pressure, but through the action of a maintained arc or flash. (Some controversy exists over the proper term but in this outline we will use arc.)

As shown in Fig. 1, the process, in its simplest form, consists of clamping two pieces of stock, free from slippage, in current carrying dies, one of which is stationary and the other movable. A suitable mechanism moves the movable die in such a manner that the ends of the parts to be welded contact. Current begins to pass between the two pieces upon contact and creates an arc.

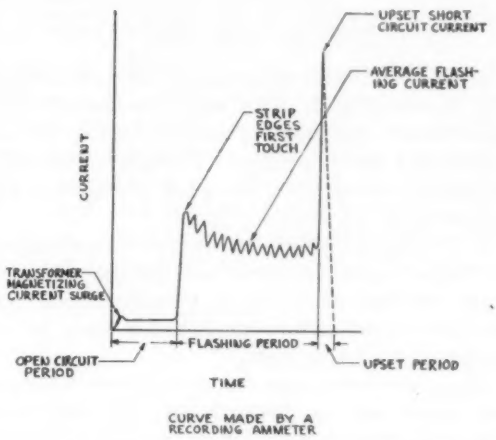

FIG. 1. Current flow during welding cycle.

The mechanism continues to maintain the arc by steadily moving the pieces together as the edges are "flashed off." This phase is called the flashing period and sufficient heat must be generated so that at the end of the flash period, the steel immediately behind the molten surface is in a plastic condition. An upset action suddenly butts, or upsets, the two pieces of material in such a manner that the molten steel is extruded to the edges of the joint forming a rim or "flash."* This action also forcibly bonds the plastic steel parts together producing a forged weld zone. Current is cut off at approximately the same time the upset starts. Fig. 1 illustrates a typical current *versus* time cycle of a flash weld. This procedure is applicable to parts having approximately the same area of contact on each part. Where the ends or shapes vary, special heating or die design is necessary to produce satisfactory welds.

Equipment

Three general types of equipment are available for the flash butt welding process.

1. Manually operated machines, in which the operator uses a lever to actuate the die motion. A thumb switch on the operating lever may be used to control the transformer current, or a limit switch may be inserted in connection with the motion of the slide to control the current automatically.

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* "Flash" is commercial terminology and should not be confused with the flashing cycle or period.

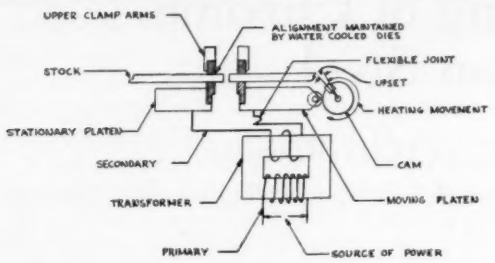

FIG. 2. Schematic diagram of flash butt welder.

2. Motor driven automatics of the type schematically shown in Fig. 2. This type of machine affords precision control over many of the variables involved and permits high speed operation. It requires little skill on the part of the operator, but setup is important in establishing new procedures.

3. Hydraulically operated automatics generally permit higher upset pressures and quicker set-up time where a multiplicity of jobs are to be performed. However, the initial investment is higher than for comparable motor driven units.

Any of the above types of machines may be furnished with hand, air, or hydraulically operated clamps. Clamping pressure depends upon the nature of the work being welded and must insure positive freedom from slippage. Best designs usually incorporate provision for carrying the welding current equally to both the upper and lower dies, so that the parts being welded will be heated uniformly. Another desirable feature is die adjustment without the use of shims, so that the work may be readily aligned. This eliminates the necessity of keeping elaborate records and stocks of shims of various thicknesses and shapes to compensate for slight errors in dies and die wear. Where a wide variety of work is expected, requiring many different styles of clamping devices and dies, it may be advisable to consider equipment having T-slotted face plates to which any style of clamping device may be attached.

The KVA "nameplate" rating is not necessarily a good method of determining the welding capacity of a machine. The KVA rating is used by the Resistance Welder Manufacturer's Association to indicate the temperature rise of a transformer, based on 50 per cent duty cycle at the nameplate rated capacity of the machine. The electrical welding ability of a given machine is largely determined by the secondary voltage, and by the impedance of the transformer and secondary circuit at that voltage. The actual KVA output of a welder may be three or four times the nameplate rating during upset, and this is entirely normal due to the low duty cycle inherent in the welding operation on a "floor-to-floor" basis.

VARIABLES AFFECTING THE WELD

(*a*) *Heat Regulator on Transformer.* It is obvious that the greater the power input into the welding transformer, which is adjusted by heat regulator, the more heat generated. The transformer output should be so adjusted as to permit ready flashing. Insufficient power output prevents proper flashing and results in a slag inclusions or poorly fused weld. Too great a power output produces "blow out" during flashing, which may cause "pin holes."

(*b*) *Flashing Speed.* In general, the greater the flashing speed, the colder the weld. Increasing flashing speed requires adjustment of other variables to maintain heat.

(*c*) *Amount of Material Flashed Off before Upset.* Increasing this variable increases the amount of heat generated.

(*d*) *Point of Current Cut-off.* This may be caused to occur before, after, or precisely at the point of upset. In welding materials with wide plastic ranges, the point of current cut-off may be carried partially into the upset thus extending the welding capacity of a given machine. At this writing, the possibility of maintaining the current flow into the upset in welding chrome-molybdenum steel has not been thoroughly investigated. Some experiments have indicated that this is not possible, as the work tends to blow out, causing pin holes. A gradual, rather than the commonly employed abrupt upset, may be a means of eliminating pin holes. The point of adjustment of current cut-off in welding chrome-molybdenum steel is of prime importance and must be determined with great care. In welding mild steel a relatively wide range of current cut-off will still result in satisfactory welds if other factors are properly balanced.

(*e*) *Magnitude and Speed of Upset.* The amount of upset controls the extrusion of molten oxidized metal and hence the purity or quality of the weld. The greater the heat generated during flashing, the greater the upset required. Excessive upset may not be objectionable so far as the weld is concerned. On motor driven machines however, a setting which would produce excessive speed or magnitude of upset may prevent proper fusion of the weld due to failure of the cam to revolve through the upset block. This must be corrected by reducing the amount of upset, slowing down the rotation of the flashing and upset cam, or increasing flashing time, which may require readjustment of other variables. Chrome-molybdenum steel requires somewhat higher upset pressures than mild steel. This is attributed to lower thermal conductivity, preventing the heat from flowing as readily from the flashing surface back into the material being welded. Narrower plastic range and greater hot compressive strength also necessitate higher upset pressure. All of these factors will be discussed in analyzing the properties of chrome-molybdenum steel.

(*f*) *Shape of Upset Block (on Motor Driven Welders).* Apparently little knowledge is available regarding this factor with reference to welding chrome-molybdenum steel. Generally an attempt is made to produce a sound weld by using available contour, and shape of

upset block is varied only as a last resort by trial and error. Some experiments are being conducted now on this variable.

(*g*) *Preheat.* This may be accomplished by introducing a reduced current prior to welding, and permits extending the capacity of a given welder. Excellent welds have been obtained on X-4130 (using equipment incapable of producing the flash burn-off and upset normally employed) by electrically heating the work prior to flashing. Such electrical preheating requires accurate control of timing, contact area and current, and for this reason should be generally avoided. Production welds have also been made using gas furnace preheating to approximately 1100°F. It is advisable to consider other variables, such as part or die design or machine settings, before resorting to this procedure.

Table 1 summarizes the above variables. The general effect on the weld of increasing one factor at a given machine setting, maintaining all other factors constant, is indicated on the right of the table.

In addition to the above variables the amount of stock extending beyond the dies affects the amount of heat generated, since that section of the pieces being welded is in the secondary of the transformer circuit. The thermal effect of water cooled die contact with reference to the weld point is also a factor. Parts having like cross-sections should extend the same distance

TABLE 1

Chart of Welding Variables

Increase	Weld*
Transformer—Heat regulator	Hotter
Flashing speed	Colder
Amount of material flashed off before upset	Hotter
Time of current flow determined by point of current cut-off	Hotter
Magnitude and speed of upset (within welding limits)	Colder
Shape of upset block	Untried
Preheat	Hotter

* This should be interpreted in the light of the foregoing discussion.

beyond the edge of the dies. Unlike parts may be brought up to fusion temperature simultaneously by uncovering the heavier piece and covering up the lighter piece as much as possible with the dies. In all cases, this distance must be determined empirically as it is based on both the cross-sectional and surface area.

The contact area between the dies and the work itself is of lesser importance except in welding very light or very heavy work. On very light sections, increasing the die contact area actually cools the work faster. On heavy work, an insufficient die contact area may prevent satisfactory welding by restricting the flow of current.

COMPARISON OF WELDABILITY OF CHROME-MOLYBDENUM AND MILD STEEL

In addition to the process variables, the physical characteristics of the chrome-molybdenum steels have a definite effect on the welding procedure.

The standard aircraft chrome-molybdenum steels, SAE, X-4130 and 4140, have the chemical analysis shown in Table 2 as compared with carbon steel.

The addition of the two alloying elements and the increase in carbon range are the only major composition changes. Both chromium and molybdenum are strong carbide forming elements. This property contributes to the strength and hardness values essential for an aircraft steel. Chromium has a moderate effect on the hardenability and a strong effect on the grain size and

TABLE 2

	X-4130	4140	Mild Steel
Carbon	.25–.33	.35–.42	.10–.30
Manganese	.40–.60	.60–.90	.30–1.00
Phosphorus	.04 max.	.04 max.	.045 max.
Sulfur	.05 max.	.05 max.	.055 max.
Chromium	.80–1.10	.80–1.10	...
Molybdenum	.15– .25	.15– .25	...

toughness of steel. To this may be added an increase in the high temperature strength property. Molybdenum has a strong influence on the hardenability, toughness and high temperature strength. Both elements readily form oxides particularly during any operation which depletes the carbon content, such as the flashing period during the welding process.

These characteristics result in a high hot compressive strength and a tendency toward oxide inclusions in the weld. It is evident that immediately following the flashing, a sudden impact with sufficient force to extrude all traces of oxidized molten metal must be exerted. The required impact during upset is approximately 25 per cent greater than that necessary for carbon steel. Fig. 3 illustrates the thermal condition of the

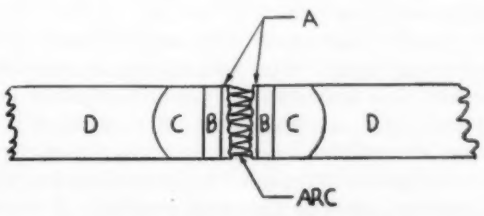

FIG. 3. Thermal condition of steel during flashing.

work immediately prior to upsetting. A represents the molten surface, B the plastic range, C the heat affected zone and D the relatively unaffected area. Fig. 4 illustrates welds made under varying conditions. (1) was made through use of electrical preheating on the welder; (2) used no preheat but a high flash and upset (note very heavy extrusion); (3) is an unsatisfactory weld made with no preheating. A weld produced through the use of furnace preheat is shown in (4). Welds were produced experimentally to develop satisfactory procedure.

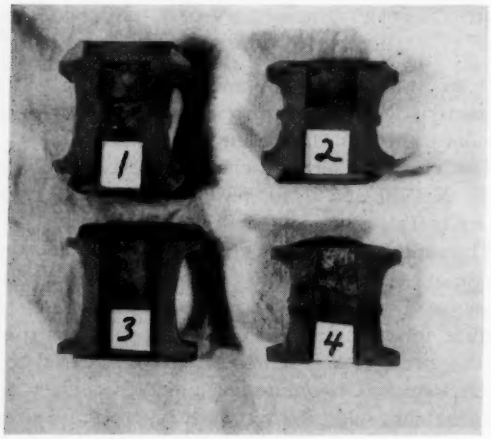

FIG. 4. Photomacrograph of well cross sections. (1), (2) and (3) normalized after welding (4) "as welded."

One factor which bears upon successful weld procedure is the possibility of trapping some of the oxidized metal in the weld. If the plastic range is not of sufficient depth, the very suddenness of the impact, coupled with the hot compressive strength of the metal behind the weld zone, may extrude and bond the faces so rapidly that all the molden slag is not eliminated, even though the work is apparently welded. One method used to eliminate this is a long flash and heavy upset which actually extrudes some of the plastic metal out of the weld interface. The force required for a weld of this type is obviously affected by the narrow plastic range of chrome-molybdenum steels. To produce satisfactory extrusion and subsequent weld, the metal immediately adjacent to the molten flash must be in an accurately controlled plastic condition. Carbon steel, with its wide plastic range, lends itself readily to this extrusion, producing slag free welds with a much lower upset force.

A properly made flash butt weld produces a very narrow weld zone. After normalizing, the area across the weld zone has relatively uniform structure and a junction is not readily apparent. This is shown in Fig. 5, where the weld zone runs horizontally across the center of the photomicrograph. An incomplete weld showing oxide inclusion at the outer periphery of the weld due to insufficient extrusion is illustrated in Fig. 6. The weld zone runs vertically across the center of the micrograph. The white area is the decarburized surface of the parts being welded.

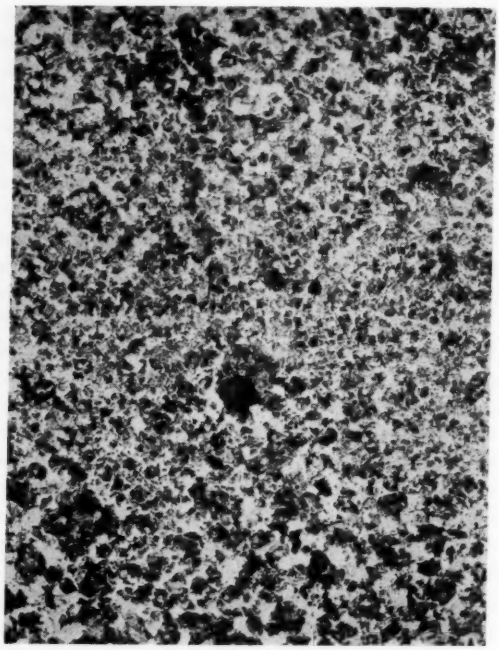

FIG. 5. Micrograph of weld after normalizing. ×100 nital etch.

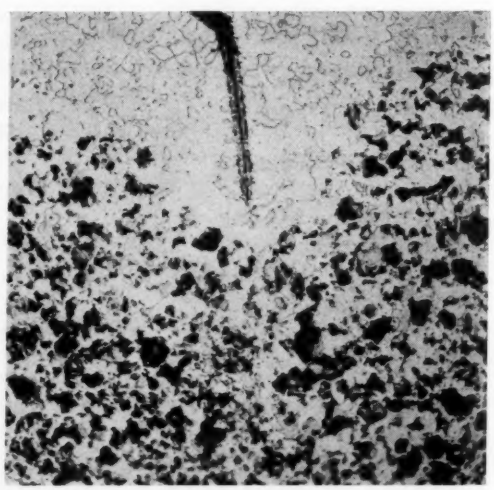

FIG. 6. Incomplete flash weld. ×100 nital etch.

The method of the weld formation creates, in the weld zone, physical properties equal to those of the parent metal. This fact in itself should prove of extreme interest to the designer of aircraft. The fatigue strength, impact strength and general physical properties are superior to those produced by other common aircraft welding procedures. Actual tests performed on aircraft push-pull rods have in every case, where properly

welded, resulted in failure in areas removed from the weld.

Empirical tests have shown that the heat treat condition of the metal has no apparent effect on the weldability. If any effect is present, it is so slight as to be imperceptible in the welds. The air hardening characteristics of chrome-molybdenum steels however, produce a much harder condition in the heat affected area of the weld provided no preheat is used. Normalized steel with a Rockwell B95 will show a hardness of Rockwell C40 to 45 in the weld zone. If parts are preheated, the area across a weld of 4140 steel has relatively uniform hardness of Rockwell C28.

In many cases, normalizing or heat treating after welding is not essential. This is particularly true where the part has been preheated. If certain properties are desired or if the weld zone is to be machined after welding, a normalizing treatment is recommended. This subsequent heat treatment cannot, in most cases, be satisfactorily performed in the welder, chiefly because of unequal heat distribution around the part. The side nearest the transformer tends to become excessively hot and may blow out under certain conditions. Any heat treatment should be performed in a furnace. After normalizing, heat treatment to produce any desired physical property may be employed.

Any effect on welding, resulting from the initial condition of the metal (whether wrought or forged) is not apparent. The greater possibility for segregation and stratification in forgings may affect the weld. No data are available at present to confirm this. Variations in grain flow may also exert some influence. More difficult welding conditions might exist where the direction of grain flow is parallel to the surfaces being welded. It is possible that other variables involved in this process are of such magnitude as to make this factor negligible.

Very limited information is available on the thermal characteristics of chrome-molybdenum steel as they affect the weldability. It is known that the rate of thermal conductivity is lower than in mild steel. This affects the ease of formation of the plastic range and necessitates the use of longer flashing periods or preheating. In some cases where the die contact is near to the weld area, it is virtually essential to preheat, particularly on large sections. Forgings, with such shape as to eliminate the possibility of sufficient extension of material beyond the dies, may require preheating for satisfactory welding. In such cases, the part should be redesigned to provide enough metal for a flash burn-off capable of generating the necessary initial heat. The B.t.u. input into the work during welding results from the heat generated during flashing, and if the parts cannot be redesigned, the next step is preheating. The flashing period not only affects the B.t.u. input, but the amount of time available for the heat to be transmitted back from the arcing surface. This condition, along with other variables resulted in the long flash period at present in use on chrome-molybdenum steel.

Since this process is basically electrical, some consideration must be given to the electrical properties of chrome-molybdenum steel. As shown by the graph in Fig. 7, the electrical conductivity of X-4130 steel is lower than mild steel. This results in greater internal resistance but reduces the current available for flashing. It would appear that a slight increase in secondary voltage over that required for mild steel is necessary to produce sufficient current for proper arcing. This is offset, however, by the tendency of this material to form blow holes at high secondary voltage. The arc forming characteristics and skin effect are also electrical variables that affect the weldability although these may be very slight. The skin effect tends to cause current flow on the outside of the pieces being welded. Uneven initial space between the parts being welded, unless excessive, does not seriously impair the

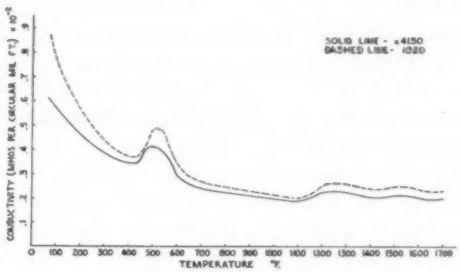

FIG. 7. Comparison of conductivity of chrome-molybdenum steel and carbon steel.

flashing. The first points to touch create an arc which starts to burn away the area of first contact, eventually resulting, as the parts move closer together, in arcing between two parallel surfaces. Faces which are nearly parallel prior to the flashing cycle result in more even initial flashing. In cases where the metal available for "burn-off" is limited, greater care in spacing will be necessary.

PRESENT PRACTICE IN FLASH BUTT WELDING CHROME-MOLYBDENUM STEEL

A study of the variables involved in flash welding and the inherent properties of chrome-molybdenum steel indicate that a number of critical factors exist. Common practice in flash welding this steel, therefore, incorporates a relatively long flash burn-off period, and a large upset at heavy pressure to minimize these critical factors. In some instances, this common practice has proven a disadvantage due to the resulting heavy extrusion of flash, and procedures peculiar to the requirements of the part have been set up. For example, such a special procedure has been used in welding aircraft engine mount lugs, where the stress on the weld is quite small, and where light flash is of great importance due to subsequent machining operations.

Destructive testing of large numbers of samples has indicated that even though infrequent pin holes or small voids occur in the weld through using a light flash procedure, the strength of the joint is more than sufficient to take care of the maximum stress developed. The point to consider is that while a 100 per cent weld can be obtained, it may not be necessary for a particular joint, and an altered procedure may be used to obtain the lowest possible unit cost of finished piece.

It is essential that the secondary voltage of the welder is not excessive, as too high a voltage tends to form deep blow holes in the material during flashing. These pin holes may be so large that it is hard to forge them together during the upset. Secondary voltage in excess of 8 or 9 volts may result in serious trouble.

Past experience of the aircraft manufacturer or the builder of the welding equipment, considered in the light of foregoing discussion, is the starting point in arriving at the proper welding procedure for chrome-molybdenum steel.

The first step is to visualize a suitable set of welding dies. If the welding operation is other than of a simple nature, or if it involves any doubtful points, it is advisable to make up an inexpensive set of welding dies, from rolled or cast copper. These dies may be used for conducting experiments to prove their design. On low production or on welds producing little die wear copper may be used for final dies. Full hard cold rolled copper being harder than cast copper is preferable. On most high production work, or where dies are in close proximity to the flash or subject to large flash exposure, Class II or III R.W.M.A. alloy should be used.

All experimental welds which are visually satisfactory should be subjected to physical and metallurgical examination. A weld to be visually satisfactory should have a generous uniform extrusion of flash, with no blow holes and little or no external cleavage line at the center of the joint. Refer to Fig. 4. In determining the machine settings it is advisable to make adjustments in the general order set forth in the chart of welding variables. (See Table 1.)

Factors to Consider in Design and Application of This Process

(*a*) *Part Design.* Identically shaped rolled sections, with clean surfaces, present the easiest form for flash welding, due to their uniformity both physically and chemically. Forgings must be thoroughly cleaned, preferably with shot or grit blast, to insure good electrical contact. If external split dies are to be used on forgings, then forging tolerances must be such as to permit good die fit. This is seldom feasible; therefore, dies, if possible, should be made to fit a machined surface on a forging.

(*b*) *Dimensions of Parts Prior to Welding.* This is determined by the amount of material necessary for flashing and upset, and may be ascertained in one of three ways.

1. Past experience.
2. Submission for recommendations or test to a reputable manufacturer of flash welding equipment.
3. Trial and error on available equipment.

(*c*) *Tolerances of Finished Piece.* In many cases ±.010 in. can be consistently produced on automatic welding machines without the necessity of subsequent machining. Closer tolerances are possible in some cases. This possibility should be investigated with reference to the particular type of equipment to be used.

(*d*) *Strength of Joint.* 100 per cent of parent metal strength can be achieved if necessary. A flash weld is the only type of weld which at present can be used in tension such as on aircraft tie rods. Chrome-molybdenum is as weldable as low carbon steel; however, in the "as welded state" it is harder in the heat affected zone than mild steel. Parts preheated to approximately 1200°F. will result in a nearly uniform hardness across the weld. The welded area will respond to heat treatment or normalizing in exactly the same manner as the unwelded sections.

(*e*) *Amount of Flash.* This may be an important consideration, if drilling or machining is required in the welded area. Chrome-molybdenum flash is quite hard and shows little or no response to heat treating. If a procedure is used where a large amount of flash is extruded, then high speed production drilling through this area may be impractical due to the difficulty of annealing the flash. A procedure should be developed to minimize flash or to remove it as fast as it is formed. On mild steel, an air blast has been used for this purpose. This practice, however, is questionable on chrome-molybdenum steel due to its air hardening characteristics.

(*f*) *Speed of Production.* On small or medium sized parts, production speeds of 200 to 350 welds per hour with one operator on an automatic welder are not at all unusual. At this time, the value of such speed is apparent.

(*g*) *Low Unit Costs.* No other welding method presents such low unit cost. The principle item of cost is labor. Power and maintenance expense is negligible.

Although at first glance the many peculiar conditions which exist in flash butt welding may appear to offer a serious problem, the process is not difficult. The possibilities in the use of this welding process in the mass production of aircraft challenge aircraft engineers to consider its advantages in future design, or present redesign, and make applications where conditions warrant. It must be remembered that among the prerequisites for the use of this process at the present time are large production, relative simplicity of part design, proper equipment, and a knowledge of the variables of the welding process.

Bending and Torsional Design Charts for Round Chrome-Molybdenum Tubing*

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ABSTRACT

In this paper design charts based on Figs. 4.20 and 4.22 of the ANC-5 are developed. These may be used for the design of round chrome-molybdenum tubing either in bending or torsion alone, or under combined bending and torsion. The general case of combined bending and torsion is simplified by use of the "equivalent" moments method and is treated in detail. Several examples illustrating the use of the charts are included. Some recent systematic combined bending and torsion tests on representative tube sizes are found to substantiate the design charts satisfactorily.

INTRODUCTION

AN IMPORTANT USE of round aircraft tubing is as a torsion carrying member. Unfortunately, instances in aircraft structures where tubing is subjected to torsion alone are few. More frequently the stresses are of the combined bending and torsional type. The supporting points rarely coincide with the point of application of the torque which in itself may be introduced by an eccentric transverse load. Often there are additional direct transverse loads. The most common applications are found in airplane control columns and surfaces, *i.e.*, aileron, elevator, and rudder torque tubes.

The reader may be familiar with the column design charts, pages 4–21 to 4–34 ANC-5,[3] originally developed by O. E. Ross. The ease of application of these charts accounts for their universal acceptance. It was the writer's desire to develop similar charts to simplify the bending and torsion problem.

The "equivalent moment" method of analyzing combined bending and torsional stresses has been taught in Machine Design courses for some time and was developed primarily for the design of solid circular shafting. As a result, this method appears in several texts.[1,2] Fundamentally, this method presents nothing new in the way of analyzing stresses; it merely simplifies design procedure. For convenience and consistency of notation and in order that its application herein may be more easily understood, the "equivalent moment" method is reproduced below.

To check the included design charts, some limited combined bending and torsion tests on a representative group of round chrome-molybdenum tubing were carried out by A. Moricca. The results, considered later in this paper, were particularly encouraging and the writer expresses indebtedness to his former student for this material.

THEORY

The symbols and formulas used are taken directly from the ANC-5.[3]

In a system subjected to combined bending and torsion:

Maximum shear stress $f_{s_{max.}} = \sqrt{f_s^2 + (f_n/2)^2}$ ANC-5 (1:8)

Maximum normal stress $f_{n_{max.}} = (f_n/2) + f_{s_{max.}} = (f_n/2) + \sqrt{f_s^2 + (f_n/2)^2}$ ANC-5 (1:9)

For combined bending and torsion $f_n = f_b$ (no axial load).

Also for round rods $y = r$ and $I_p = 2I$.

Taking $f_s = Tr/2I$; ANC-5 (1:3) and $f_b = Mr/I$; ANC-5 (1:6).

Substituting Eqs. 1:3 and 1:6 in Eqs. 1:8 and 1:9

$$f_{s_{max.}} = [M\sqrt{1 + (T/M)^2}](r/2I) \tag{1}$$

$$f_{n_{max.}} = (M/2)[1 + \sqrt{1 + (T/M)^2}](r/I) \tag{2}$$

or

$$f_{s_{max.}} = T_e r/2I \tag{3}$$

$$f_{n_{max.}} = M_e r/I \tag{4}$$

where

$$T_e = M\sqrt{1 + (T/M)^2} \tag{5}$$

$$M_e = (M/2)[1 + \sqrt{1 + (T/M)^2}] \tag{6}$$

Eq. (3) is similar to Eq. ANC-5 (1:3) and indicates that the maximum shear stress may be found from the ordinary torsion equation, Eq. (1:3), if an "equivalent" torsional moment T_e found from Eq. (5) is used. Similarly, the maximum normal stress may be found from the ordinary bending Eq. (1:6) if an "equivalent" bending moment M_e evaluated by Eq. (6) is used.

It is well to note that T_e and M_e have numerical significance only and represent fictitious or "equivalent" moments except for the special cases of bending or torsion alone. Then the "equivalent" moment may be taken equal to the corresponding bending or torsional moment.

Presented at the Structures session, Tenth Annual Meeting, I.Ae.S., New York, January 28, 1942.

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If the maximum allowable stresses are known the required maximum section modulus I/r may be found analytically from Eqs. (3) and (4) and a corresponding tube size could then be obtained from standard tube section properties tables.

For relatively brittle and solid shafting a further simplification in design procedure may be made. It is mentioned briefly here to complete the theory. If, as in shafting, the design may be based on the ultimate tensile and shear stresses which are constants a useful design criterion is obtained by dividing Eq. (2) by Eq. (1)

$$f_{n_{max.}}/f_{s_{max.}} = 1 + (1/\sqrt{1 + (T/M)^2}) \qquad (7)$$

For a fixed ratio of the ultimate stresses F_n/F_s, there is only one value of T/M which will satisfy Eq. (7). If the T/M ratio exceeds this value, then the shear stresses alone become critical and only T_e need be investigated. Similarly for T/M's less than the criterion only M_e is critical. Then for each T/M ratio, either Eq. (3) or Eq. (4) alone need be investigated to determine the required tube size.

It must be kept in mind that "failures of round tubes of usual sizes when subjected to bending (or torsion) are usually of the plastic instability type. In such cases the criterion of strength is the modulus of rupture as derived from test results through the use of $f = M_c/I$ (or $f = Tr/2I$)."[4] The use of Eq. (7) could be applied to tubes, therefore, but the ratio of allowable stresses F_n/F_s is no longer a constant, and this might complicate matters somewhat.

However, the ratio of the allowable stresses for tubes does simplify the design further. Niles and Newell[5] state that "f_s will always exceed $f_n/2$. Study of ANC-5 Figs. 4.20 and 4.22 will show that for nearly all practical sizes of tubes the allowable shearing stress in torsion is not over half the modulus of rupture. If we consider the former to be the allowable value of $f_{s_{max.}}$ and the latter the allowable for $f_{n_{max.}}$, the shearing stress will be the critical one." The use of final design charts presented below is so simple that it is not much more work to determine both M_e and T_e and solve both Eqs. (3) and (4) by charts and then use the larger tube size indicated.

Design Charts

A simplification in required calculations may be made to Eqs. (5) and (6). Let

$$K = \sqrt{1 + (T/M)^2} \qquad (7)$$

Then Eqs. (5) and (6) may be written

$$T_e = MK \qquad (8)$$

$$M_e = (M/2)(1 + K) \qquad (9)$$

The variation of K with T/M as expressed in Eq. (7) is plotted in Fig. 1. Then T_e and M_e can be computed directly from Eqs. (8) and (9).

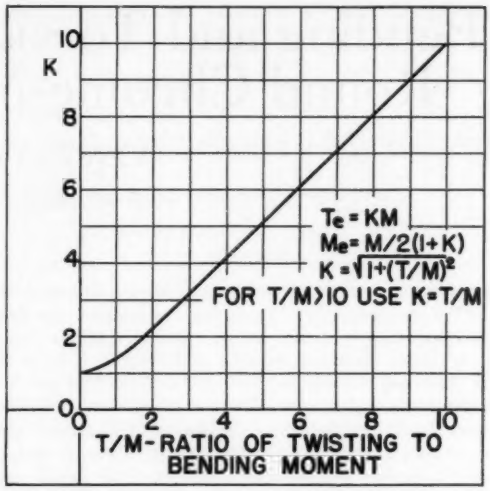

Fig. 1. Determination of equivalent twisting (T_e) and equivalent bending (M_e) moments.

Accepted conservative design practice[5] for tubes in bending and torsion has been to keep the maximum combined normal or shear design stresses below the modulus in bending or torsion, respectively, and finally checking the margins of safety based on these stresses by means of the "stress-ratio" interaction curves ($R_b^2 + R_s^2 = 1$ for round tubing). This is the method followed and substantiated by limited tests.

The actual design charts, therefore, are based on the moduli of bending and torsion appearing as Figs. 4.20 and 4.22 in the ANC-5.[3] Simple expressions can be obtained which describe these curves with sufficient accuracy.

Fig. 4.20 of the ANC-5 was taken from tests reported in A.C.I.C. No. 686.[6]

A logarithmic plot of the results of several of these tests shows a straight line variation of the bending modulus with the ultimate tensile strength. This may be expressed as $F_b = K_1(F_{tu})^x$. Calculations for the determination of the average value of the logarithmic slope x and the proportionality constant K_1 can be made from data in Fig. 1—of A.C.I.C. No. 686.[6] This gives $F_b = K_1(F_{tu})^{1.06}$ where the variation of K_1 with D/t is shown in Fig. 2.

Fig. 4.22 of the ANC-5 may be written $F_{st} = K_2 F_{tu} \cdot (L/D)^{-.10}$ where the variation of K_2 with D/t is shown on Fig. 3. Analytically $K_2 = (D/t)/[-.330 + 1.048(D/t) + 0.01276(D/t)^2]$. This information is taken from an Air Corps publication,[7] the basis for ANC-5 Fig. 4.22.

With Figs. 2 and 3 it becomes a relatively simple matter to determine the allowable M_e and T_e from Eqs. 3 and 4. These calculations are used in conjunction with the tube section properties[5] to obtain the final design charts Figs. 4 through 13.

Figs. 4 to 8, inclusive, show the allowable "equivalent" bending moment M_e for various tube sizes as a

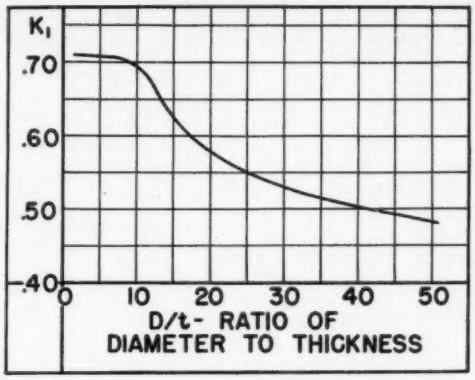

FIG. 2. Constant K_1 for bending modulus of rupture formula $F_b = K_1(F_{tu})^{1.08}$; where K_1 is a function of diameter to thickness ratio (D/t) and F_{tu} is ultimate tensile strength.

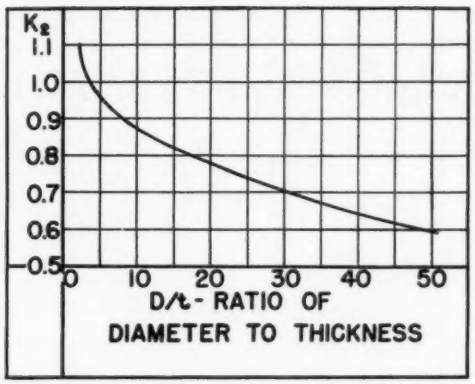

FIG. 3. Constant K_2 for torsional modulus of rupture formula $F_{st} = K_2F_{tu}(L/D)^{-0.10}$; where K_2 is a function of diameter to thickness ratio (D/t) and F_{tu} is ultimate tensile strength; L/D is length to diameter ratio.

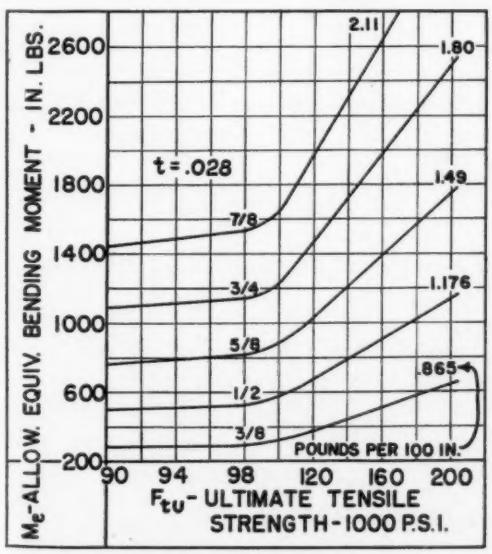

FIG. 4. Allowable bending moments for round chrome-molybdenum steel tubing. $t = .028$.

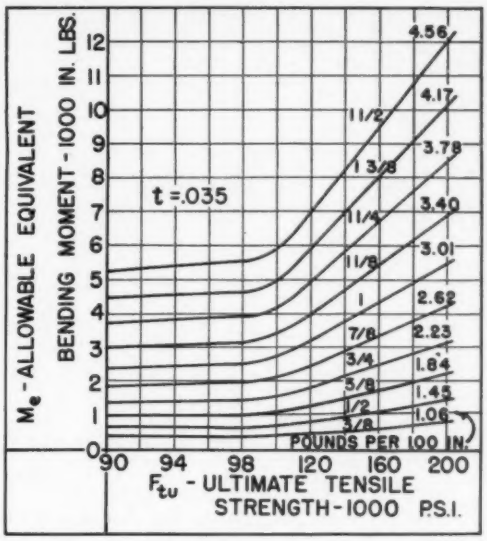

FIG. 5. Allowable bending moments for round chrome-molybdenum steel tubing. $t = .035$.

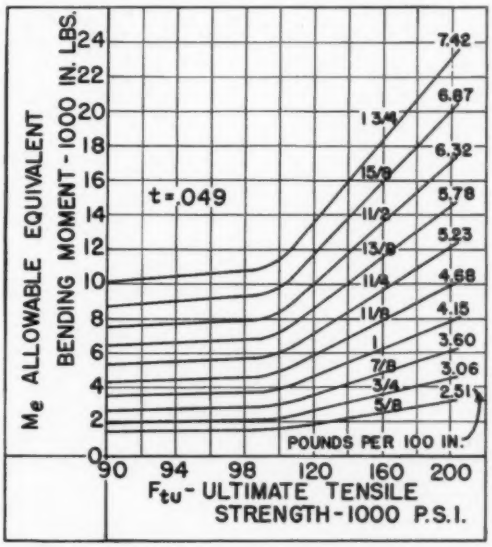

FIG. 6. Allowable bending moments for round chrome-molybdenum steel tubing. $t = .049$.

function of the ultimate tensile strength. Figs. 9 to 13, inclusive, show the allowable "equivalent" twisting moment T_e for the various tube sizes as a function of tube length for an ultimate tensile strength of 100,000 lbs. per sq.in. The allowable T_e for an ultimate tensile strength other than 100,000 lbs. per sq.in. is the chart T_e(other U.T.S./100,000). The use of the charts is quite straightforward and is most easily demonstrated by several examples which follow.

EXAMPLES

1. Find the required tube size of normalized chrome-molybdenum which will carry the designated combined

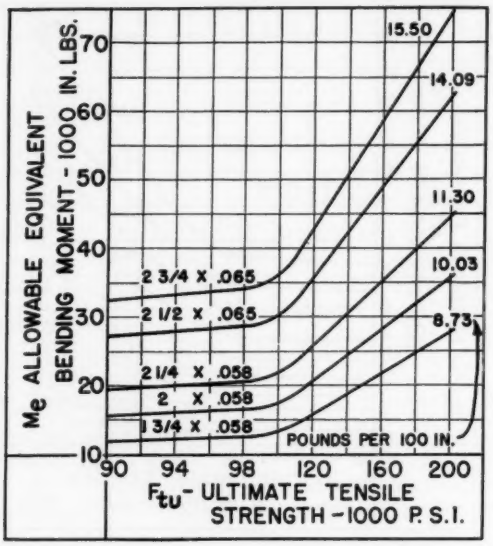

FIG. 7. Allowable bending moments for round chrome-molybdenum steel tubing. t = .058 and .065.

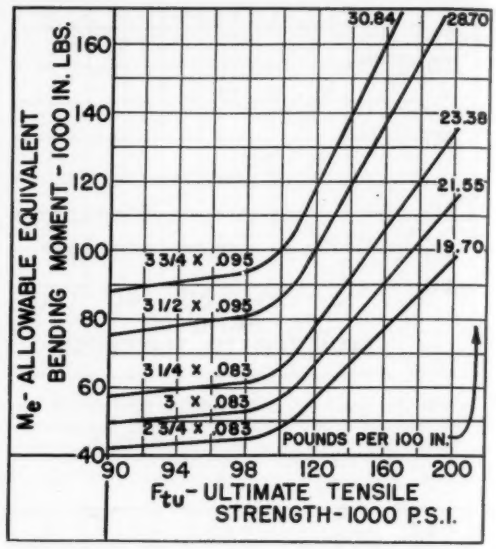

FIG. 8. Allowable bending moments for round chrome-molybdenum steel tubing. t = .083 and .095.

bending and torsional loads. Table 1 indicates the step by step procedure.

TABLE 1

Method	Sta.	0	20	30	40
Design Loads from (1)	T	1000	2500	3000	4000
External Force System (2)	M	4000	2500	1500	1000
(3) Compute T/M = (1) ÷ (2)		0.250	1.00	2.00	4.00
(4) Find K from Fig. 1		1.02	1.41	2.25	4.12
(5) Compute $T_e = KM$ for U.T.S. = 95,000		4080	3530	3380	4120
(6) Compute T_e for U.T.S. = 100,000 = (5) × 100/95		4300	3720	3560	4330
(7) Compute $M_e = (M/2)(1 + K)$		4040	3010	2440	2560
(8) Find reqd. tube for largest M_e = 4040 at Sta. 0		From Fig. 5, U.T.S. = 95,000; USE 1 3/8 × .035, $M_{e\ allow.}$ = 4540 From Fig. 6, U.T.S. = 95,000; USE 1 1/8 × .049; $M_{e\ allow.}$ = 4450			
(9) Find reqd. tube for largest T_e = 4330 at Sta. 40		From Fig. 10, L = 40; USE 1 3/8 × .035; $T_{e\ allow.}$ = 4420 From Fig. 11, L = 40; USE 1 1/8 × .049; $T_{e\ allow.}$ = 4430			

The lightest tube which will safely carry the above loads is 1 3/8 × 0.035.

The margins of safety for the 1 3/8 × 0.035 tube may be computed from the "equivalent" moments thus:

At Sta. 0, M.S. = (4540/4040) − 1 = 12 per cent
At Sta. 40, M.S. = (4420/4330) − 1 = 2 per cent

By ordinary trial and error design methods the same tube size would have finally been decided upon. This will be evidenced by an independent check of the margins of safety based on the ANC-5 moduli Figs.

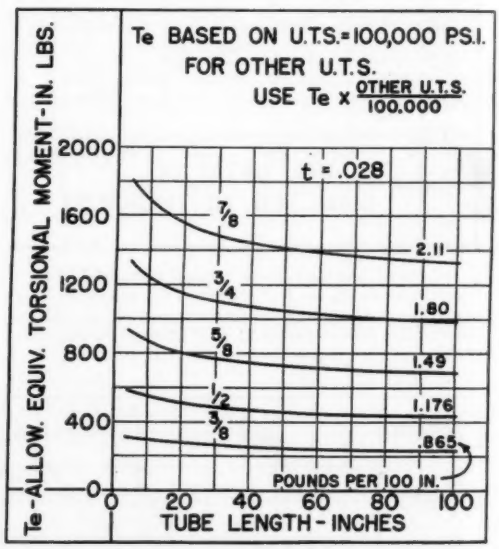

FIG. 9. Allowable torsional moments for round chrome-molybdenum steel tubing. t = .028.

4.20 and 4.22 and the "stress-ratio" interaction curve $R_b^2 + R_s^2 = 1$.

For 1 3/8 × .035 tube: D/t = 39.3; L/D = 29.1; $Z = I/y$ = .0481. From Fig. 4.20 ANC-5 F_b = 94,500 lbs. per sq.in. For comparison F_b is also determined from $F_b = K_1(F_{tu})^{1.06}$. From Fig. 2

K_1 = 0.500
F_b = 94,500 lbs. per sq.in.

From Fig. 4.22 ANC-5

F_s = 43,700 lbs. per sq.in.
$F_s = K_2(Ftu)^{-.10}$ = 43,700 lbs. per sq.in.

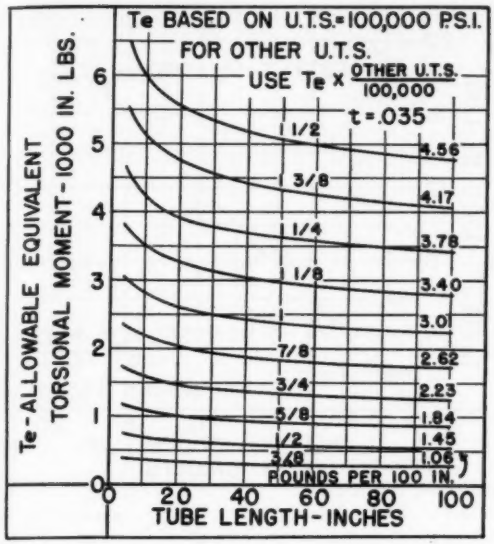

FIG. 10. Allowable torsional moments for round chrome-molybdenum steel tubing. t = .035.

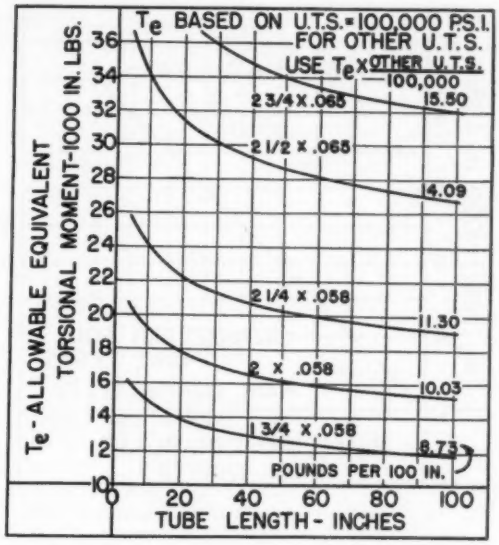

FIG. 12. Allowable torsional moments for round chrome-molybdenum steel tubing. t = .058 and .065.

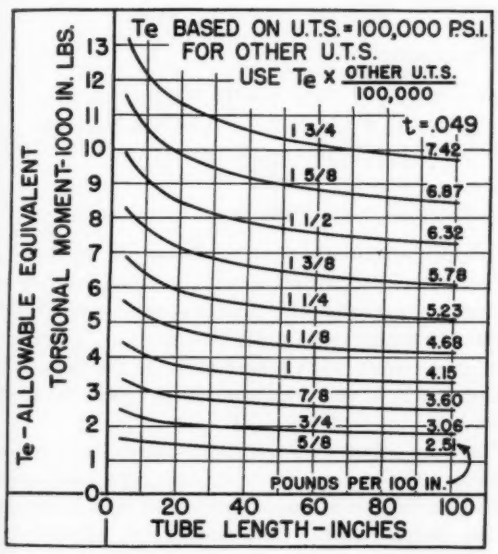

FIG. 11. Allowable torsional moments for round chrome-molybdenum steel tubing. t = .049.

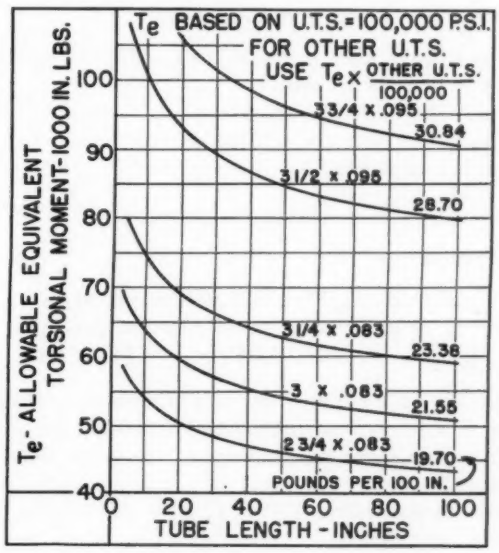

FIG. 13. Allowable torsional moments for round chrome-molybdenum steel tubing. t = .083 and .095.

At Sta. 0

f_b = 4000/0.0481 = 83,100 lbs. per sq.in.
f_s = 1000/2 × 0.0481 = 10,400 lbs. per sq.in.
R_b = 83,100/94,500 = 0.880
R_s = 10,400/43,700 = 0.237

M.S. = $(1/\sqrt{R_b^2 + R_s^2}) - 1$ = 10 per cent as compared with 12 per cent by charts

At Sta. 40

f_b = 1000/0.0481 = 20,800 lbs. per sq.in.
f_s = 41,700 lbs. per sq.in.
R_b = 20,800/94,500 = 0.220
R_s = 41,700/43,700 = 0.953
M.S. = 2 per cent as compared with 2 per cent by charts

2. Find the required size of a chrome-molybdenum tube heat treated to 125,000 lbs. per sq.in. with a maximum design bending moment alone of 2000 in.lbs. For bending alone

$$M_e = M_{max.} = 2000 \text{ in.lbs.}$$

From Fig. 5 the required tube size is $^7/_8 \times 0.035$

$$M_{allow.} = 2560 \text{ in.lbs.}$$

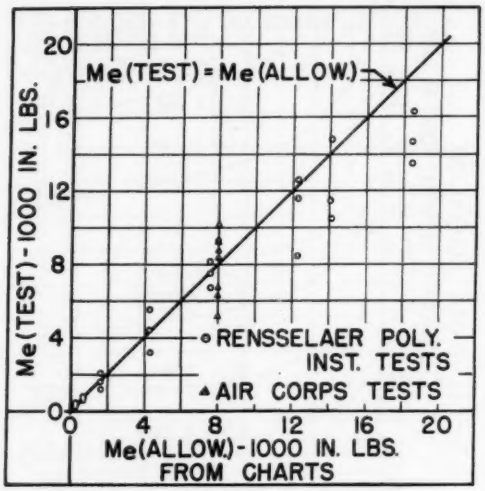

FIG. 14. Experimental check of M_e (equivalent bending moment) design charts.

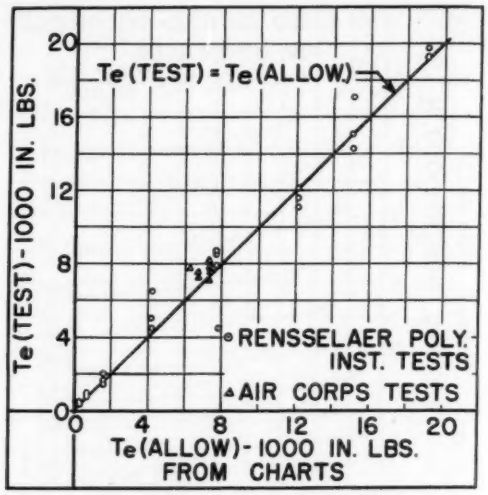

FIG. 15. Experimental check of T_e (equivalent torsional moment) design charts.

From Fig. 6 the required tube size is $^3/_4 \times 0.049$

$$M_{allow.} = 2700 \text{ in.lbs.}$$

The lightest tube is $^7/_8 \times .035$; M.S. = (2560/-2000) − 1 = 28 per cent.

For $^7/_8 \times .035$ tube 125,000 lbs. per sq.in. U.T.S.: $D/t = 25$; $Z = I/y = 0.0187$.

From Fig. 4.20 ANC-5

$$F_b = 140{,}000 \text{ lbs. per sq.in.}$$

For comparison

$$F_b = K_1(F_{tu})^{1.06} = 139{,}500 \text{ lbs. per sq.in.}$$
$$f_b = 2{,}000/.0187 = 107{,}000 \text{ lbs. per sq.in.}$$
$$\text{M.S.} = (140{,}000/107{,}000) - 1 = 31 \text{ per cent}$$

3. Find the required size of a chrome-molybdenum tube 50 in. long heat-treated to 125,000 lbs. per sq.in. with a maximum design torsional moment alone of 2500 in.lbs.

For torsion alone $T_e = T_{max.} = 2500$ in.lbs. for U.T.S. = 125,000.

$$T_{max.} = (100/125) \times 2500 = 2000 \text{ in.lbs. for U.T.S.} = 100{,}000$$

From Fig. 10 the required tube size is $1 \times .035$;

$$T_{allow.} = 2730 \text{ in.lbs.}$$

From Fig. 11 the required tube size is $^7/_8 \times .049$;

$$T_{allow.} = 2600 \text{ in.lbs.}$$

The lightest tube is $^7/_8 \times .049$;

$$T_{allow.} \text{ (U.T.S. 125,000)} = 1.25 \times 2600 = 3250 \text{ in.lbs.}$$
$$\text{M.S.} = (3250/2500) - 1 = 30 \text{ per cent}$$

For $^7/_8 \times .049$; 125,000 lbs. per sq.in. U.T.S.;

$$D/t = 17.85$$
$$Z = I/y = .0249$$
$$L/D = 57.1$$

From Fig. 4.22 ANC-5

$$F_s = 66{,}100 \text{ lbs. per sq.in.}$$

For comparison

$$F_s = K_2(F_{tu})(L/D)^{-.10} = 66{,}100 \text{ lbs. per sq.in.}$$
$$f_s = (2500/2 \times .0249) = 50{,}100 \text{ lbs. per sq.in.}$$
$$\text{M.S.} = 66{,}100/50{,}100 = 32 \text{ per cent.}$$

TEST DATA

To substantiate the design charts, A. F. Moricca carried out a series of systematic combined bending and torsion tests under the writer's supervision.[8] The results are summarized in Figs. 14 and 15. The largest tube sizes tested failed prematurely at the jaws of the testing machine and are therefore not included in this summary.

The only other available information on combined bending and torsion is from an Air Corps publication.[9] Unfortunately, only one of these tube sizes is included in the design charts. The results are referred to as Air Corps tests.

In Figs. 14 and 15 the M_e and T_e computed from tests have been plotted against the M_e and T_e allowed by the design charts. The 45° line would represent perfect agreement between the design chart allowable values and the experimental test points.

CONCLUSIONS

It has been shown[9] that the allowable maximum normal and shear stresses for combined bending and torsion are slightly higher than the moduli taken from uncombined bending or torsion tests. The design charts presented, in keeping with accepted practice, are based on the moduli of uncombined bending and torsion tests. The agreement between the tests and

allowable moments taken from the design charts as shown in Figs. 14 and 15 indicate this method of design to be quite satisfactory.

Margins of safety based on the ratio of allowable to design "equivalent" moments are found to be in good agreement with those found by the stress-ratio method. Therefore, minimum margins of safety may also be determined directly from these design charts.

By using the actual bending and twisting moments in place of M_e and T_e values the design charts are also directly applicable to the design of tubes in uncombined bending or torsion.

References

[1] Kimball and Barr, *Elements of Machine Design*, pages 44–51, J. Wiley and Sons, Inc., New York, 1935.

[2] Timoshenko, S., *Strength of Materials*, Part I, pages 269–272, D. Van Nostrand Co. Inc., New York, 1930.

[3] Army-Navy-Civil Committee on Aircraft Requirements, *ANC-5 Strength of Aircraft Elements*, U.S. Govt. Printing Office, Oct. 1940.

[4] *ANC-5*, Paragraphs 1.422 and 1.423.

[5] Niles, A. S., and Newell, J. S., *Airplane Structures*, Vol. 1, pages 198–204, J. Wiley & Sons, Inc., 1938.

[6] Brown, C. G., and Carpenter, F. M., *Strength of Chrome-Molybdenum Tubing Under Bending Due to Transverse Loading*, Air Corps Information Circular No. 686, July 10, 1934.

[7] *Engineering Section Memorandum Report No. M-56-2622*, Parts I and II, Air Corps publication, Materiel Division, Wright Field, Dayton, Ohio.

[8] Moricca, A. F., *An Experimental Investigation of Round Chrome-Molybdenum Tubing Under Combined Bending and Torsion*, Senior Thesis, Rensselaer Polytechnic Institute, Troy, N. Y., 1941.

[9] Harvuot, R. E., *Allowable Shear from Combined Bending and Torsion in Round, Elliptical, and Streamlined Tubes and Allowable Normal Stress from Bending in Thin Walled Tubes*, Air Corps Information Circular No. 669, June 30, 1932.

Gas Exchange in the Lungs at High Altitudes

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Gas Exchange in the Lungs at High Altitudes

THE EXCHANGE OF GASES between capillary blood and air in the depths of the lungs occurs across a membrane so thin as to afford virtually unopposed movement to carbon dioxide and oxygen. This membrane has been compared in area to a tennis court; its character and its surface are such that the quantity of carbon dioxide moving through it in a gentle zephyr of 200 cc. per minute during rest may be increased 20 times during exercise. Yet neither in rest nor in exercise does the pressure gradient for carbon dioxide exceed 1 or 2 mm. of mercury. The proof for this comes from analysis of simultaneous samples of alveolar air—air taken from the depths of the lungs—and of arterial blood drawn from an artery without loss or gain in its gas contents.

The conditions for oxygen exchange are somewhat different. Ordinarily, at ground level the partial pressure of oxygen in alveolar air, the alveolar pO_2, is higher by about 20 mm. Hg than the pO_2 in blood that reaches the arteries. For several reasons it is generally agreed that this is not a diffusion gradient. Haldane and Priestley[1] pertinently remark that if there were really such a gradient in rest the diffusion theory must fall because it would be impossible to account for the fact that but little drop in arterial oxygen occurs in exercise, though there may be a fifteen fold increase in oxygen transfer. It is also significant that an increase of 20 mm. Hg in the pO_2 of inspired air has little effect on the amount of oxygen taken up by the blood. The hypothesis has been advanced by Bock and his associates[2] that as the oxygen saturation of hemoglobin approaches completion chemical and physical processes within the capillary may be slow enough to prevent the attainment of full equilibrium. At ordinary atmospheric pressures blood reaches a saturation of from 94 to 96 per cent of capacity, whereas it would be nearly 99 per cent if the alveolar oxygen pressure were reached in the blood.

This technical point has been emphasized here because it has been the source of some misunderstanding; many have supposed that since there is this apparent pressure head of 20 mm. Hg under ordinary circumstance it is to be anticipated under all circumstances. Such is far from the case; as soon as a moderate degree of oxygen lack is experienced—enough to lower the arterial oxygen saturation to 90 or 92 per cent—practically full equilibrium is attained between alveolar air and blood in so far as partial pressure of oxygen is concerned. The fact that this can occur without any change in the character or amount of pulmonary ventilation strengthens the view that the combination of hemoglobin with oxygen is slow enough to be a limiting factor at 95 per cent saturation but is fast enough to be excluded as a limiting factor at or below 90 per cent saturation.

It shall be assumed, therefore, that if the arterial oxygen saturation is below 90 per cent the sum of the partial pressures of the various gases in alveolar air will equal the sum of the partial pressures of the same gases in arterial blood. It is the purpose of this paper to present in support of this assumption experimental evidence obtained at simulated altitudes up to 44,000 ft. in the pressure chamber and to show what adaptations enable man, while breathing pure oxygen, to withstand such experiences.

Granting the attainment of full equilibrium of gases between lungs and blood as soon as the pinch of anoxemia makes itself felt, there is an added means of protection that comes to man's support in emergencies. This is the mechanism that regulates pulmonary ventilation. Ordinarily, regulation is effected by carbon dioxide, but in the emergency of anoxia carbon dioxide is thrown to the wind and the need for oxygen, mediated through the carotid body, provides a regulatory stimulus. The gain is twofold:

(1) Increased pulmonary ventilation keeps the carbon dioxide content of arterial blood at a lower level than usual; hence, the blood is made more alkaline and so in turn hemoglobin acquires a greater affinity for oxygen. This occurs because the chemical nature of hemoglobin is such that with increasing alkalinity more and more oxygen will combine with it at a given partial pressure of oxygen, provided one remains within the range of partial saturation.

(2) Increased pulmonary ventilation with air of constant composition raises the partial pressure of oxygen in alveolar air by partial displacement of other gases. If air is being respired, the gain will depend on displacement both of carbon dioxide and of nitrogen. If oxygen is breathed, the gain comes only from partial displacement of carbon dioxide.

Presented at the Physiologic Problems (Part I) session, Tenth Annual Meeting, I.Ae.S., New York, January 29, 1942.

* Aero Medical Research Unit, Equipment Laboratory, Experimental Engineering Section, Materiel Division.

TABLE 1

Arterial Oxygen and Carbon Dioxide at High Altitudes

Subject	Oxygen Supply	Pressure Altitude, ft.	Arterial Oxygen Saturation, %	Arterial CO_2 Vols. %	pH	Arterial pCO_2 Mm. Hg	Arterial pO_2 Mm. Hg	Arterial $pCO_2 + pO_2 + pH_2O$, Mm. Hg
P	Air	17,000	80.4	46.8	7.38	41.0	47	135
S	Air	18,000	70.7	47.5	7.51	31.5	33	111
Gs	Air	18,000	72.3	41.5	7.50	29.6	34	111
D	Pure oxygen	35,000	95.9	..	..	..	..	...
G	Pure oxygen	35,000	94.3	..	..	..	..	...
P	Pure oxygen	37,500	93.0	44.9	7.40	39.0	70	156
Gn	Pure oxygen	37,500	94.8	46.8	7.37	41.9	81	170
S	Pure oxygen	37,500	93.8	47.3	7.39	41.0	70	158
J	Pure oxygen	37,500	94.3	..	..	..	..	...
Ge	Pure oxygen	39,000	85.9	43.0	7.38	37.8	54	139
D	Pure oxygen	39,000	91.8	42.7	7.38	36.8	68	152
L	A-8 full flow	40,000	89.9	42.3	7.39	37.2	61	145
H	A-8 full flow	40,000	91.8	37.2	7.42	30.5	64	141
Ge	A-8 full flow	40,000	84.9	38.6	7.46	29.4	48	124
N	A-8 full flow	40,000	90.6	43.7	7.35	41.2	66	154
T	A-8 full flow	40,000	80.7	46.5	7.45	35.6	43	126
P	A-8 full flow	40,000	87.9	43.8	7.41	37.0	45	129
J	Pure oxygen	40,000	90.5	45.6	7.43	36.0	60	143
P	Pure oxygen	40,000	88.3	44.2	7.50	32.0	52	131
Gn	Pure oxygen	41,000	86.7	45.2	7.47	33.0	50	130
D	Pure oxygen	41,000	86.1	47.8	7.32	46.8	58	152
Ge	Pure oxygen	41,000	86.4	41.5	7.41	34.5	53	134
Gn	Pure oxygen	42,000	88.5	47.4	7.41	38.8	56	142
F	Pure oxygen	42,000	83.4	47.6	7.41	39.5	49	135
P	Pure oxygen	42,000	77.0	46.4	7.38	41.5	43	132
Ge	Pure oxygen	43,000	80.6	44.5	..	..	..	...
W	Pure oxygen	43,000	86.1	38.1	7.56	23.4	45	115
H	Pure oxygen	43,000	77.7	42.0	7.51	29.7	38	115
P	Pure oxygen	43,000	69.5	..	..	..	..	...
J	Pure oxygen	44,000	74.9	43.6	7.46	32.3	38	117
Gn	Pure oxygen	44,000	72.9	44.9	7.47	33.0	36	116
S	Pure oxygen	44,000	68.9	46.2	7.47	34.2	33	114

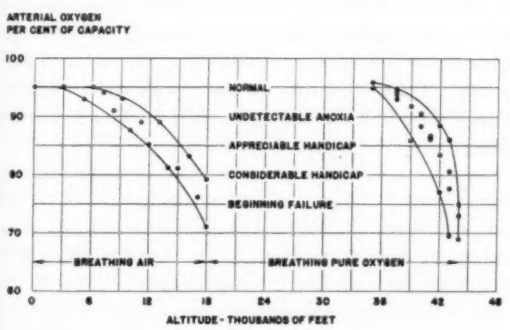

FIG. 1.

No matter how great the increase in pulmonary ventilation, the partial pressure of water vapor in the depths of the lungs, the alveoli, remains constant so long as the body temperature is constant. Hence, for man it must be assumed that the pH_2O in the alveoli is 47 mm. Hg. At ground level this is inconsequential, but when the barometric pressure has dropped to 142 mm. Hg, as at 40,000 ft., it is a hard fact. At that total pressure, even when breathing pure oxygen, there is the necessity of subtracting 47 and having left a total of 95 mm. Hg to cover the partial pressures of both carbon dioxide and oxygen in alveolar air and in arterial blood.

Parenthetically, it is worth remarking here that breathing pure oxygen at 44,000 ft. is not equivalent physiologically to breathing at ground level an air-nitrogen mixture having the same partial pressure of oxygen. The handicap at low pressure is much greater than at high pressure because of the facts outlined above. Many physiologists have overlooked this point and have made incorrect deductions from laboratory studies of anoxia induced by administering air-nitrogen mixtures.

It has been suggested above that the respiratory response to anoxia renders the blood more alkaline. Expressed in other terms, the acid-base balance is upset. Should one take steps to prevent this? The only practical means of preventing this disturbance have been tested—the addition of carbon dioxide to the inspired air or oxygen. There is no doubt about the advantage at 18,000 ft. of breathing air containing 3 per cent CO_2 over breathing air alone, but as much, if not more, advantage is gained by adding the same percentage of oxygen. At 40,000 ft. altitude there is no advantage whatever in adding CO_2 to the oxygen that is supplied to the mask. Many tests at 40,000 ft. have revealed that admixing 10 per cent of CO_2 (equivalent to 2 per cent at ground level) cannot be detected subjectively by resting subjects and seems oppressive

to some subjects working on the bicycle ergometer. If there was any effect on arterial oxygen uptake it was a decrease rather than an increase. It can be stated categorically that no carbon dioxide should be added to oxygen supplied for high altitude flight. These statements do not imply that the present Army oxygen equipment with its economy bag is unsound. This bag collects the air from the dead space but it does not collect enough CO_2 from the alveolar spaces to produce a noticeable effect on respiration.

The question as to what limits are set to high altitude flight by man's respiratory system is a crucial one. This is now answered on the basis of arterial punctures made at various simulated altitudes in the pressure chamber ranging from 35,000 to 44,000 feet. The data are summarized in Table 1 and the arterial oxygen saturations are shown in Fig. 1. At 37,500 ft. the arterial oxygen saturation ranges from 93 to 95 per cent if pure oxygen is breathed. These values are the same as seen in man at sea level breathing air, although the alveolar oxygen pressure could not have exceeded 70 to 80 mm. Hg—values ranging from 20 to 40 mm. lower than at sea level. The evidence with regard to alveolar oxygen tension is obtained indirectly. Analysis of arterial blood yields values for its pO_2 and pCO_2. At 37,500 ft. their sum plus 47 (the accepted value for pH_2O) averages, in three men, 161 mm. as compared with 159 mm. total external pressure. If there were an appreciable pressure gradient of oxygen, the sum of the partial pressures in the blood would be less than the total atmospheric pressure. This presupposes equilibrium with regard to partial pressure of carbon dioxide—an assumption that is strongly supported by a wealth of experimental evidence. Particular attention has been directed to the observations at 37,500 ft. because there is no evidence of a considerable pressure gradient even though the arterial oxygen saturation is above 93 per cent. This indicates that when pure oxygen is supplied at high altitudes full equilibrium can be expected across the alveolar membrane if the saturation is at or below 93 per cent.

At 39,000 to 40,000 ft. the arterial saturation, breathing pure oxygen, ranges from 86 to 90 per cent with arterial oxygen tensions of 52 to 60 mm. Here anoxemia becomes evident; it compares with altitudes of about 9000 to 12,000 ft. breathing air.

At 41,000 ft. the range in arterial saturation is from 86 to 87 per cent in three subjects. At 42,000 ft. the range is from 77 to 88; at 43,000, from 69 to 86; and in three subjects at 44,000 ft., 69 to 75 per cent. At this last altitude we have passed the limit of effective activity and are in a precarious state; a comparable altitude without oxygen equipment is 18,000 ft. These facts are somewhat at variance with previously held opinions based on assumptions and extrapolations. The error in those assumptions depended, in part, on failure to appreciate the possibility of nearly complete equilibrium in the diffusion of oxygen into the blood

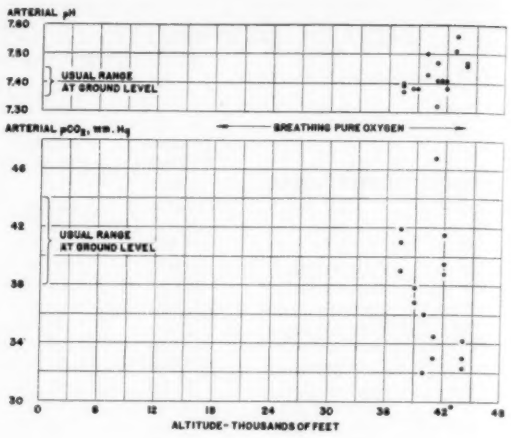

FIG. 2.

and, in part, to no allowance having been made for increased pulmonary ventilation, although the importance of this response was established years ago by Haldane and other physiologists.[1]

The evidence for increased pulmonary ventilation is seen in the decreasing partial pressure of carbon dioxide in arterial blood as the altitude increases (Fig. 2). The normal range for arterial pCO_2 at ground level is from 38 to 43 mm. Hg. All the values at 37,500 ft. are within this limit. Above that altitude the arterial pCO_2 declines progressively to a range of from 32 to 34 mm. at 44,000 ft. Since the CO_2 combining capacity of the blood does not change even at 44,000 ft. (see Table 1), a decline in pCO_2 implies a decline in the ratio of free carbonic acid to combined carbonic acid. In harmony with this it is seen that the arterial pH, a measure of the alkalinity of the blood, remains normal up to 39,000 feet and tends to shift farther toward the alkaline side at higher altitudes (Fig. 2).

These data on the arterial saturation while breathing pure oxygen at these extreme altitudes are being used as a standard to which the performance of oxygen equipment can be referred. For example, six inactive men using present Army equipment at 40,000 ft. were found to have arterial saturations of from 81 to 92 per cent. Furthermore, at altitudes above 40,000 ft., while the subject on whom the arterial punctures were made breathed pure oxygen from a gasometer, the observer who made the punctures used the present Army equipment. While he attempted no hard work at 44,000 ft., he was able to rise from a sitting to a standing posture once a minute in order to make readings on a gasometer gauge. Sustained hard work would have been impossible, since the present equipment permits the admixture of air as soon as the respiratory minute volume is much increased.

A matter of much practical importance is the degree to which physical activity is limited at these extreme altitudes, granting that pure oxygen is supplied. A number of tests have been carried out at 40,000 ft. in

TABLE 2

Altitude, ft.	Oxygen Capacity, Vols. %
37,500	21.1
39,000	20.2
40,000	21.6
41,000	20.1
42,000	20.8
43,000	20.9
44,000	20.2

which the subjects rode a bicycle ergometer while breathing pure oxygen from a gasometer. The grade of work used required an oxygen consumption of a little more than 1 liter per minute. After a steady state was reached and while work still continued, a sample of arterial blood was drawn. Examination of these samples in eight men revealed saturations ranging from 83 to 90 per cent in seven men and 72 per cent in the eighth man. This latter subject was found to have tuberculosis and this probably accounted for his poor performance. The mean value for the other seven was 87.8, which is about the value expected in man in the resting state at this altitude.

Of the other significant measurements reference will be made here only to the oxygen combining capacity—*i.e.*, the total available hemoglobin. After long exposures to anoxia—as in those who live in high altitudes—there occurs a remarkable increase in hemoglobin amounting to from 50 to 70 per cent of ground level values. This change requires more time than is available in high altitude flights. While some animals may respond to anoxia by a rapid increase in blood hemoglobin that depends on its mobilization from reservoirs, no such response has been seen in man. The present experiments are no exception. Taking the average value for oxygen combining capacity as from 20 to 21 volumes per cent, the average values are given in Table 2.

CONCLUSIONS

Exchange of gases in the lungs of man has been studied at pressure altitudes up to 44,000 ft. while breathing oxygen. There was considerable handicap at 44,000 ft., but four men survived six exposures lasting from 13 to 30 min. without collapse.

Breathing oxygen at 40,000 ft. involves no greater pulmonary ventilation than at ground level, but above that height anoxia leads to deeper breathing. This produces a lower partial pressure of carbon dioxide in the lungs and an associated increase in partial pressure of oxygen and in the affinity of blood for oxygen. It is these adaptive responses that enable man to survive at 44,000 ft. in a state closely resembling that produced by breathing air of ordinary composition at 18,000 ft.

Virtual equilibrium is reached between alveolar air and arterial blood. Diffusion is not a limiting factor in rest, and even in work requiring an oxygen supply of four times the resting level the arterial saturation is well maintained at 40,000 ft.

These phenomena will not surprise physiologists who have studied human respiration at lower altitudes while breathing air. There is nothing novel nor mysterious about human respiration in an atmosphere of pure oxygen at altitudes in the neighborhood of 40,000 ft.

REFERENCES

[1] Haldane, J. S., and Priestley, J. G., *Respir tion*, Second Edition, Yale University Press, New Haven, 1935.

[2] Bock, A. V., Dill, D. B., Edwards, H. T., Henderson, L. J., and Talbot, J. H., *On the Partial Pressures of xygen and Carbon Dioxide in Arterial Blood and in Alveolar Air*, ournal of Physiology, Vol. 68, p. 277, 1929.

Midwest Student Branch Regional Meeting

SPONSORED BY THE Iowa State College Student Branch of the Institute and under the supervision of Prof. W. C. Nelson of Iowa State, the first Student Branch Regional Meeting was held on March 21 at South Bend, Indiana.

The University of Notre Dame, through the courtesy and cooperation of Prof. F. N. M. Brown, Head of the Department of Aeronautical Engineering, acted as host to the technical sessions of the meeting. Eleven colleges and universities, representing a geographic distribution over an area roughly 900 by 600 miles, cooperated to make this one of the most interesting and successful meetings ever held under the auspices of the Institute. Eighteen faculty members and 157 students represented the colleges and universities at the meeting. The faculty members present and the universities they represented are as follows: Herbert W. Reed, The Aeronautical University, Chicago, Illinois; Prof. Bradley Jones, Ray Bisplinghoff, and Hans P. Liepmann, University of Cincinnati, Cincinnati, Ohio; Philip Blenkush and George H. Tweney, University of Detroit, Detroit, Michigan; Prof. Wilbur C. Nelson, Iowa State College, Ames, Iowa; Prof. E. A. Stalker, University of Michigan, Ann Arbor, Michigan; Prof. John D. Akerman, University of Minnesota, Minneapolis, Minnesota; Prof. F. N. M. Brown, M. C. Demler, and Robert S. Eikenberry, University of Notre Dame, Notre Dame, Indiana; J. E. Arnold, University of Pittsburgh, Pittsburgh, Pennsylvania; Prof. K. D. Wood, Purdue University, Lafayette, Indiana; Prof. M. E. Collins, Tri-State College, Angola, Indiana; and E. M. Horwitz, Wayne University, Detroit, Michigan.

Registration was held on the evening preceding the day of technical meetings in the Engineering Building of the University of Notre Dame, and members and guests were given the opportunity of inspecting the aeronautical engineering laboratories of the University. A group breakfast the following morning preceded the technical sessions at Notre Dame. Eight student papers, the titles and authors of which are given below, were presented during the morning and afternoon.

Pressure Distribution by Electrical Equipotential Line—H. M. Flake, University of Cincinnati

A Rational Method of Determining the Drag of End Plates for Wind Tunnel Tests—Robert Mendelsohn, University of Detroit

Superfinish as Applied to Aircraft Engine Bearings—M. A. Sorenson, Iowa State College

A Jet Propelled Helicopter—Charles Ranson, University of Michigan

Factors Influencing the Design of Pressure Cabins—Thomas D. Matteson and W. Dale Drinkwater, University of Minnesota

The Determination of an Empirical Formula for the Radial Deflection of Long, Thick-Walled Tubes—Murray O'Toole, University of Notre Dame

Cowling Designing—Don Christopherson, Tri-State College

Aircraft Engine Cooling for Aerodynamic Efficiency—Raymond L. Zavasky, University of Pittsburgh

The facilities of the Indiana Club of South Bend were made available for a group luncheon and dinner. Major Lester D. Gardner, Executive Vice-President of the Institute, spoke at the luncheon on the functions of the Institute as related to Student and Student Branch activities.

Following the presentation of the last student paper in the afternoon technical session, Prof. John D. Akerman spoke briefly on Medicine and Aviation, stressing the importance of close cooperation in the two fields toward solving physiologic problems. Prof. K. D. Wood spoke on *Research Problems and the Universities*.

The technical sessions were closed with the showing of motion pictures on the Bell "Airacobra" and a film of the development and work of the Lockheed Aircraft Corporation.

A dinner, which was attended by 150 members and guests, concluded the day's program. William B. Stout of the Stout Skycraft Corporation was the guest speaker and spoke on the importance of continued research and experiment in aircraft design and production. Cash awards were presented to the two students who, in the opinion of an award committee, presented the best student technical papers. The first award was given to Herbert Flake of the University of Cincinnati and the second to Raymond L. Zavasky of the University of Pittsburgh. Honorariums were given to each of the other six student speakers. The Institute, in appreciation of the efforts of Profs. Nelson and Brown, presented them with reproductions of Dr. John Jeffries' rare book *A Narrative of the Two Aerial Voyages of Dr. Jeffries with Mons. Blanchard* autographed especially for the occasion by Orville Wright.

The meeting, the first of a series now planned by the Institute, was outstanding in that it was suggested, organized, and held entirely through the independent efforts of the Student Branches. The success of the meeting, made possible only through the cooperation of these Branches, is indicative of the successful functioning of the Institute's plan for Branches in fostering an interchange of ideas between the Student Members.

Institute Notes

Detroit Section Meeting, March 4

The joint meeting of the Detroit Section of the Institute and the Engineering Society of Detroit on Wednesday, March 4, was the largest technical society meeting ever held in that city.

The speaker of the evening was Igor I. Sikorsky, Managing Engineer, Vought-Sikorsky Aircraft Division, United Aircraft Corporation, who spoke on the development and testing of his VS-300 helicopter and illustrated his lecture with motion pictures of the craft in flight, taking off, and landing. Five hundred persons attended the dinner in the banquet hall which preceded the meeting. Before the meeting started the main auditorium seating 1000 was filled. A total of over 1700 people attended, the overflow being accommodated in smaller meeting rooms. A second showing of the motion picture that illustrated the lecture was given in the main auditorium for those who had not been able to see the first presentation.

Mr. Sikorsky expressed the belief that this type of aircraft might create one of the world's largest postwar industries by providing a safe and flexible means of individual transportation that would not compete with automobiles, airplanes, and boats but would fill in the gaps between the spheres of transport service furnished by these means. The influence that the helicopter might have in encouraging a more efficient and healthful dispersal of centers of settlement rather than an increase in the congestion of large cities was mentioned.

The meeting was held in the recently opened Horace H. Rackham Educational Memorial Building at Farnsworth and Woodward Avenues in Detroit. This beautiful and completely modern building serves as the headquarters for the University of Michigan's Extension Service and Institute of Public and Social Administration, as well as for The Engineering Society of Detroit.

Harvey M. Merker, President of the Detroit Engineering Society; Ralph H. Upson, Chairman of the Detroit Section; and William B. Stout, Stout Skycraft Corporation, presided at the dinner and lecture. The meeting proved so successful that the officers have made plans to hold an aviation meeting once a month, and Glenn L. Martin, President of The Glenn L. Martin Company, is scheduled to be guest speaker at the meeting on April 8.

Gifts to the Archives

The collections in the Institute's Aeronautical Archives, including the reference and lending libraries, are being enlarged constantly by gifts from generous friends who wish to make the aeronautical material that they have available for interested persons through the library research facilities of the Institute. Gifts received during the past two months have added to the historical collections, have supplied missing items from series of reports and periodicals, and have increased the files of new material on technical subjects.

In one section of the Archives, consisting of American aeronautica prior to 1900, four items of special interest to aeronautical historians have been added. Mrs. E. S. Harkness presented a photostat of an original letter in her possession written in Paris by Benjamin Franklin to Dr. Ingenhaus, of Vienna, on January 16, 1784, dealing with balloons in war. George R. Cooley, of Albany, New York, gave to the Archives an original of a book published in that city in 1825—*Memorial on the Upward Forces of Fluids, and Their Applicability to Several Arts, Sciences and Public Improvements* by Edmond Charles Genet. The author is the "Citizen" Genet, Minister of the First French Republic to the United States, who came to this country in 1793 and remained until his death in 1834. A copy of *Aerial Navigation* by D. Caulkins, M.D., published in Toledo, Ohio, in 1825, was presented by Miss Leona Replogle of that city. Prof. F. K. Kirsten donated a bound photostatic copy of a book by Jerry Wraunlow, published by the Noya Kima Company, Seattle, in 1898, purporting to be a scientific treatise, though a highly colored one as indicated by the title—*Newly Discovered Properties of the Cycloid; or the Curve of Unknown Force. Recording the Remarkable Discoveries of Anke, the Japanese Wizard.*

The following publications were received for the Institute libraries: books, pamphlets, and magazines on plastics from R. J. Barbour, The Bakelite Corporation; two copies of Report No. 9 of the Society of Aeronautical Weight Engineers on *Aircraft Balancing and Center of Gravity Control* from W. A. Semion of the S.A.W.E.; bound volume of the first twelve issues of Pan American Airways house organ *New Horizons* from William Van Dusen; magazine articles on plywood from Thomas D. Perry, Resinous Products & Chemical Co.; aeronautical books and pamphlets from Robert E. Ellis, Standard Oil Company of New Jersey, and from Gordon C. Sleeper, Reynolds Company.

Edward P. Warner presented four 1938 issues of *Revue Aeronautique Internationale*, a copy of *The Great German Air Raids on Great Britain*, 1914–1918, by Capt. J. Morris, and the 1934 edition of *Metal Aircraft Construction*, by Marcus Langley. Mr. William H. Dey of Bildey Products Company gave some Air Corps seals to be added to the insignia and medal collection and four books: *A Journey in Other Worlds* by John Jacob Astor (1894), *Aero Club of America Yearbook for 1907*, *Navigating the Air* (1907), and *The Story of the Airship* by Hugh Allen.

The Institute is indebted to the McGraw-Hill Publishing Company and Leslie E. Neville, Editor of *Aviation*, for a recent gift of a large amount of aeronautical material which includes 47 books, 110 Government reports, and a number of back issues of periodicals and pamphlets.

The exhibits of models and pictures in the Aeronautical Archives, which are always of interest to visitors at the Institute's headquarters, have also received additions. Paul Bewshea of British Overseas Airways presented a large cutaway model of an Imperial Airways flying boat mounted in a case. A demonstration model gyroscope was sent on behalf of the Sperry Gyroscope Company by J. A. Fitz. William R. Enyart of Simmonds Aerocessories contributed a print of the oil painting "Sinking of the Kensington Court" by the English artist, Hesbeth Hubbard. It portrays the first aerial rescue at sea of the survivors of submarine attack in the present war.

Although all new books and periodicals are added to the Institute's collections as soon as received from the publishers, gifts of publications of both historical and contemporary interest are gratefully received. They may be added to the Burden Reference Library, The Paul Kollsman Library, or the Pacific Aeronautical Library. Duplicate books are welcome as they are useful for exchange with other libraries and to supply extra loan copies of titles in constant demand.

News of Institute Members

Milton B. Ames, Jr., is Assistant to the Director of Research of the N.A.C.A. in Washington. He had previously been an Instructor in Aeronautics for the College of William and Mary Extension Division in Norfolk, Va.

Richard F. Bache, M.I.Ae.S., Engineer on the Staff of the C.A.A., is on temporary duty with the Materiel Division, Army Air Forces.

E. R. Breech, M.I.Ae.S., has been elected President of Bendix Aviation Corp., succeeding **Vincent Bendix,** M.I.Ae.S, Mr.

Breech resigned as Vice-President in charge of Aviation for General Motors Corp.

Edward Burd is on the staff of Emerson Electrical Mfg. Co. as a Preliminary Design Engineer.

Robert E. Burke, formerly Junior Stress Analyst with The Glenn L. Martin Co., is now a layout Draftsman for Stinson Aircraft Div., Vultee Aircraft, Inc.

Fred Chang recently completed his work at the University of Michigan for his Master's degree and is now a Stress Engineer with Langley Aviation Corp.

Robert A. Cornog is engaged in research work at the Palmer Physical Laboratory of Princeton University.

Robert R. Dansfield has left United Air Lines, where he was a First Officer, to become an Engineering Test Pilot for Boeing Aircraft Co.

Homer W. Dotts, formerly Layout Engineer, Airplane Div. (Buffalo Plants), Curtiss-Wright Corp., is now Senior Group Engineer.

Capt. Jean H. DuBuque, M.I.Ae.S., who was Chicago Branch Manager of Aero Insurance Underwriters, is on active duty with Army Air Forces Service Command.

Christopher Dykes, Technical Officer for British Overseas Airways Corp., is temporarily assigned as representative of the R.A.F. Middle East Communications at Municipal Airport, Baltimore.

Claude M. Fligg, A.F.I.Ae.S., has been on leave for several months from his position as Aeronautical Engineer with the C.A.A. to serve as a Lieutenant in the Navy. He is in command of a mine-sweeper.

H. R. Foottit, M.I.Ae.S., has accepted a commission as Flying Officer, Aeronautical Engineering Branch, Royal Canadian Air Force. Born and educated in British Columbia, Mr. Foottit was, until recently, an Engineering Instructor at Ryan School of Aeronautics and had previously been a Patent Engineer with Vultee Aircraft.

Kenneth Forney has been transferred from the Aero Engine Laboratory of the Naval Aircraft Factory, where he was a Junior Aeronautical Engineer, to Assistant Aeronautical Engineer, Bureau of Aeronautics, Navy Department in Washington.

Ernest F. Gamache, formerly Executive Director, Air Youth of America, is the Personnel Director of Simmonds Aerocessories, Inc.

Harold S. Gillespie, M.I.Ae.S., a Captain on Pan American Airways System, has been transferred from LaGuardia Field to the Eastern Division of the company at Miami.

Lt. C. William Guy, formerly Junior Layout Draftsman, Lockheed Aircraft Corp., is a Base Signal Officer, U. S. Army Signal Corps, stationed in Oregon.

C. R. Haig, Jr., has left the Fairchild Aircraft Division of Fairchild Engine & Airplane Corp., where he was an Engineer, to become an instructor in the Engineering School of Spartan School of Aeronautics.

Lt. Charles S. Hughes, U.S.M.C.R., recently completed his Naval Aviation Cadet training to qualify for a commission in the Marine Corps.

Donald C. Hunt is Assistant Managing Secretary of The Engineering Society of Detroit, which now has its headquarters in the recently opened Horace H. Rackham building. He is also Instructor of Aeronautics at Detroit Institute of Technology.

Nicholas Mastrocola has been appointed an Assistant Aeronautical Engineer at the Langley Memorial Aeronautical Laboratory, N.A.C.A.

Lewis C. McCarty, Jr., M.I.Ae.S., who has been Vice-President in charge of Engineering, Central Aircraft Mfg. Co., in China since 1940, is now with Hindustan Aircraft Ltd. in India.

Formerly with Fairchild Aircraft Div., Fairchild Engine & Airplane Corp., **Jerome B. Meyer** is a Stress Analyst on the staff of Allied Aviation Corp.

M. F. Newmark, Jr., has been promoted from Inspector to Time Study Engineer with Consolidated Aircraft Corp.

Capt. F. W. Pennoyer, Jr., U.S.N., has been transferred from duty as Materiel Officer with the Support Force, U.S. Atlantic Fleet, to the Aeronautics Section, Office of Production and Materiel, Navy Department. A Fellow of the Institute, Captain Pennoyer was Head of the Engineering and Design Division, Bureau of Aeronautics, from 1937 to 1940 and served for four years as Assistant Naval Attaché in Rome. He graduated from the U.S. Naval Academy in 1915, received an M.S. degree in 1920 for postgraduate work in naval architecture at Massachusetts Institute of Technology and qualified as a Naval Aviator at the Pensacola Naval Air Station in 1923.

Announcement has been made of the establishment of the Department of Aeronautical Engineering at Princeton University under the direction of **Daniel C. Sayre,** A.F.I.Ae.S. From 1926 to 1933 he was an Instructor and then Assistant Professor of Aeronautical Engineering at the Massachusetts Institute of Technology, of which he is a graduate. He has been an editor for *Aviation*, *Technology Review*, and the Aviation Department of *Newsweek*, has been consulting aeronautical engineer for aircraft companies, and was formerly Director of the Bureau of Statistics and Information, C.A.A.

William D. Snell has left Engineering & Research Corp. to join the engineering staff of Curtiss Propeller Div., Curtiss-Wright Corp.

Robert D. Spencer, M.I.Ae.S., has been appointed Assistant Chief of Structures for McDonnell Aircraft Corp. He had been Project Structural Engineer and Senior Stress Analyst, Vultee Aircraft, Inc., for the past three years and was Chief Engineer of Tipton Aircraft Co. from 1935 until 1937 when he joined the staff of the St. Louis Airplane Div., Curtiss-Wright Corp.

C. G. Taylor, M.I.Ae.S., Chairman of the Board of Taylorcraft Aviation Corp., has resigned as consultant on all matters pertaining to the business of the company. He organized the Taylor Aircraft Co., now Piper Aircraft Corp., and also the Taylor-Young Co. which was the predecessor of Taylorcraft.

Frederick M. Thomas, A.F.I.Ae.S., has been appointed to the staff of the Aircraft Branch, Production Division, War Production Board, as a specialist in engine and propeller problems. Until his return to this country several months ago, Mr. Thomas was Engineering Manager, Airscrew Division, of The deHavilland Aircraft Co., England, where he had gone in 1934 to supervise the manufacture of Hamilton Standard metal propellers under license from the United Aircraft Corp. He joined the Research Division of United Aircraft in 1929 and has been a recipient of the Wright Brothers Medal and the Manly Memorial Medal.

On the staff of Pan American Airways System at San Francisco since January, 1941, **Ralph B. Tilney** has been transferred to Pan American Airways-Africa Ltd. He was formerly an Engineer in the Aerodynamics Dept., Airplane Div. (St. Louis Plant), Curtiss-Wright Corp.

Vernon G. Townsend, Checker in the Engineering Dept. of The Glenn L. Martin Co., has been made Chief Checker, The Glenn L. Martin-Nebraska Co.

Guy W. Vaughan, M.I.Ae.S., President of Curtiss Wright Corp., has been named chairman of an aviation industry committee to raise $500,000 for the Navy Relief Society.

Lt. Henry G. Webb, U.S. Marine Corps, has been reported missing in action since the capture of Wake Island in December and is presumably a prisoner of war in the hands of the Japanese. A graduate of the University of North Carolina in 1938, he was active in the National Intercollegiate Flying Club contests during his student years. While in training as an Aviation Cadet in the U.S. Marine Corps Reserve at Pensacola, he joined the Institute as a Technical Member. His brother is **James E. Webb,** M.I.Ae.S., Treasurer of the Sperry Gyroscope Co. At Wake Island

Lieutenant Webb was attached to Marine Fighting Squadron 211 of Marine Aircraft Group 21 which was one of the units cited by President Roosevelt on January 5 "for their devotion to duty and splendid conduct at their battle stations under most adverse conditions."

George W. Westphal has been made Chief Stress Analyst of Waco Aircraft Co. with which he has been associated since 1939.

C. V. Whitney, M.I.Ae.S., Chairman of the Board, Pan American Airways System, has been commissioned a Major in the Army Air Forces.

Paul H. Wilkinson, M.I.Ae.S., consultant on aircraft and diesel engines and author of several books on these subjects, is Head of the Army and Navy Aircraft Section, Contract Distribution Branch, Production Division, War Production Board, for the New York State region with headquarters in New York City.

I. B. Yassin, Aeronautical Engineer, is now Assistant Chief of Structures, Aeronautical Division, Snead & Co.

Student Branches

University of California. Branch officers for the 1942 spring semester are Bradford H. Wick, Chairman; Andrew C. Marshall. Vice-Chairman; Edward L. Wasson, Secretary-Treasurer. F. W. Hutchinson, Assistant Professor of Mechanical Engineering, acts as Honorary Chairman and Faculty Adviser. At a meeting held on February 12, Bradford Wick gave a talk on the polar flight of the airship Norge and showed the group some souvenirs, including the log of the flight, which were presented to the University of California in 1926 by Charles B. Stokes, one of the crew members. On March 19, Robert Grenzeback, Instructor in Mechanical Engineering at the University, spoke on aircraft production before a meeting of the Branch.

University of Detroit. Three meetings have been held since the first of the year. On January 6, Carl Schoren of the Holley Carburetor Company gave an illustrated lecture on the Holley venturi-type carburetor. Robert Mendelsohn, who had been chosen to represent the University of Detroit Branch at the technical sessions of the Midwest Student Branch Regional Meeting, made the first presentation of his paper on determination of the drag of end plates before a meeting of the Branch on February 10. At the meeting on March 18, J. W. Kinnucan, Vice-President in charge of Engineering for Continental Motors Corporation, made the annual presentation of the Continental Design Trophy to George S. Graff, a member of the Branch.

Harvard University. Because of the fact that a number of members of the Branch had been called to active military duty, a business meeting was held on March 6, electing the following new officers: William E. Brown, Chairman; Bernard F. Shattuck, Vice-Chairman; and Dr. R. von Mises, Honorary Chairman and Faculty Adviser. A new program of meetings was planned for the remainder of the school year.

Indiana Technical College. At a banquet held on February 19 in honor of graduating Branch Members, officers for the next two terms were elected as follows: William Hazard, Chairman; Ray Trout, Vice-Chairman; Jack Murray, Secretary; Elmer Boos, Treasurer. At this meeting the motion picture *Spark Plugs in Aviation* was shown. At the following meeting on March 9, the Chairman explained the purposes of the organization and received applications for new members. The Treasurer reported on the proposed purchase of a motion-picture projector for the Branch, and a committee was appointed to secure aeronautical films for future meetings. In response to the notice of the Regional Meeting for March 21 at the University of Notre Dame, 16 members signified their intention of attending.

Iowa State College. The activities of the Branch for 1942 were inaugurated by the Annual Aeronautical Banquet held on January 22, which was attended by about 100 members of the I.Ae.S. Branch and the local Pilots' Club. Arthur Jerrems, United Air Lines, gave a talk on "The Place of the Airlines in This Defense" and a film on the Royal Canadian Air Force was shown. At meetings on February 18 and March 3, plans for the delegation to the Regional Meeting were discussed and technical papers by members of the Branch were presented. Carol Fruth reported on light aircraft engines and Mervyl Sorenson read his paper on aircraft engine bearings. The latter was chosen for presentation at the Regional Meeting.

Massachusetts Institute of Technology. At a joint meeting of this Branch and the M.I.T. Aeronautical Engineers Society on February 17, Ronald Shainin, Chairman of the Branch, presented the motion-picture film *Conquest of the Air* before an audience of 150 technology students. On March 3, Otto E. Kirchner, Chief Engineer of American Airlines, was guest at a dinner meeting of the Branch and gave a talk, illustrated with slides, on the operational procedures of an airline engineering department.

Rensselaer Polytechnic Institute. At a closed meeting of the Branch on February 26, Col. Steven L. Conner of the U.S. Army Ordnance Department at Watervliet Arsenal spoke on aircraft armament, touching on the history of aerial warfare and comparing its development with that of naval warfare. He described some features of horizontal aerial bombing and of anti-aircraft gunfire from the ground and compared their accuracy. The importance of designing fighting planes around the guns to be carried was emphasized.

On March 12, Dr. P. E. Hemke, Professor A. J. Fairbanks, and V. C. Trimarchi of the R.P.I. faculty acted as judges of three student papers presented in the prize contest at the Branch meeting. William Mueller read a paper on the development and installation of extended propeller shafts in aircraft and pointed out their advantages and disadvantages. Douglas King discussed the development and future possibilities of flying boats in a report, illustrated with pictures and slides, on factors governing the design of flying boats. A paper on various types of airplane landing gear was presented by Edward Koenig which dealt mainly with tricycle landing gear and a comparison of their ground stability and other features with those of conventional types. The meeting concluded with the showing of the motion picture *Stalling Characteristics of the Lockheed 14.*

Personnel Opportunities

The Personnel Bureau serves individual members, as well as organizations seeking to employ aeronautical specialists. Any member or organization may have requirements listed without charge.

Wanted

Aeronautical Engineer to organize, supervise, and teach Engineering Defense Training courses in Dallas and Fort Worth, Texas, in program sponsored by The University of Texas. College degree, industrial and teaching experience desirable. Salary $300 per month or more, depending on qualifications. Send applications with complete personal history and photograph to M. J. Thompson, The University of Texas, Austin, Texas.

Instructors (two) familiar with airplane design, salary $2,200 a year; **Research Assistants** (two) with no teaching duties, familiar with aerodynamic research, stipend $900 plus income from research work, opportunities for graduate work; **Teaching Assistants** (three) in engine, structural and aerodynamic laboratories, stipend $900 first year, opportunities for graduate work; **Fellow** for specialized research, no teaching duties, stipend $750, opportunities for graduate work, appointment June 15. Location east with large university. Give educational background, professional experience, photograph, in letter of application. Address reply to Box 150, Institute of the Aeronautical Sciences.

Approved Aircraft School in midwest desires mechanic and engineering instructors. Furnish qualifications, experience and snapshot in first letter. Address reply to Box 152, Institute of the Aeronautical Sciences.

Airplane Designers, Stress Analysts, and Draftsmen needed for few vacancies remaining on engineering staff. At least four years' experience essential. Release will be required if now employed in similar position. Write for appointment stating education, experience, and salary. Snead & Company, Aeronautical Division, 350 Communipaw Ave., Jersey City, N. J.

Available

Aeronautical Engineer, with twelve years of practical and well-rounded experience in the aeronautical design field and with the U.S. Navy. Also instructor in aircraft design. Executive and inventive ability. Hard working. Desires position with a new or expanding concern in the capacity of chief, assistant chief, project engineer, or similar. Address reply to Box 153, Institute of the Aeronautical Sciences.

Changes in Membership

The following changes in the membership of the Institute have occurred since the publication of the previous issue of the Journal.

Elected to MEMBER Grade

Fontaine, Athanas Paul, Chief Engineer, Engineering and Development Dept., Vultee Aircraft, Inc.

Fraser, Oliver, Jr., E. E.; Aero. Engineer, Carnegie-Illinois Steel Corp.

Hartenberg, Richard Scheunemann, Ph.D.; Asst. Prof. of Mechanics, Northwestern Technological Institute.

Kelly, Thomas Nelson, B.S. in Ae.E.; Structures Engineer, Mfg. Research Dept., Vultee Aircraft, Inc.

Kramer, C. Raymond, B.S. in M.E.; Project Engineer, Brewster Aeronautical Corp.

Loring, Samuel J., B.S.; Research Engineer, Vought-Sikorsky Aircraft Div., United Aircraft Corp.

Lyman, Charles B., M.S. in M.E.; Aero. Engineer (Structures), Bureau of Aeronautics, Navy Dept.

Martin, Erle, B.S. in E.E.; Engineering Manager, Hamilton Standard Propellers Div., United Aircraft Corp.

Nordgren, Arnold William, B.S. in E.E., Testing Engineer, Bendix Products Div., Bendix Aviation Corp.

Roberts, Clifford Evans, B.S. in M.E.; Asst. Chief Engineer, The Glenn L. Martin Co.

Rohman, Eugene, B.S. in Ae.E.; Aerodynamics Dept., Vega Airplane Co.

Stevenson, Alexander Russell, Jr., Ph.D.; Staff Asst. to Vice-Pres. in charge of Engineering, General Electric Co.

Wieben, Herman Claus, Jr., Ae.E.; Chief Project Engineer, The Glenn L. Martin Co.

Elected to Industrial Member Grade

Akin, Russell Bliss, Ph.D.; Sales Development Engineer, Plastics Dept., E. I. du Pont de Nemours & Co.

Bercovitz, Bernhard, Pres. & Gen. Manager, Canadian Aircraft Instrument & Accessories, Ltd., Canada.

Bean, John Berry, B.S., LL.B.; Aviation Patent Attorney, Messrs. Bean, Brooks, Buckley & Bean.

Berry, Ethan Allen, Works Manager, Chicago Pneumatic Tool Co.

Bigelow, Maurice Hubbard, Ph.D.; Director, Technical Service Div., Plaskon Co., Inc. (See W.W. in Eng.; A. M. of S.)

Hall, Delancey Medbury, Sales Engineer, Harrison Radiator Div., General Motors Corp.

McArthur, Warren, M.E.; President, Warren McArthur Corp.

Elected to Technical Member Grade

Altseimer, John Henry, B.S. in M.E.; Stress Analyst, The Glenn L. Martin Co.

Ashton, John, Production Manager, Electrol, Inc.

Cary, Charles Oswald, Control Supervisor, Boston Area, American Airlines; Statistical Research in Aviation Medicine.

Coven, Robert Henry, Aero. Engineering Student, Parks Air College.

Enk, Eugene Sinclair, Draftsman, Airplane Div. (St. Louis Plant), Curtiss-Wright Corp.

Feigen, Morris, B.S. in C.E.; Engineer, Airplane Div. (St. Louis Plant), Curtiss-Wright Corp.

Fischer, Andrew J., B. S.; Engineer, The Continental-Diamond Fibre Co.

Groben, Philip McConnell, M.E.; Salvage Engineer, Lockheed Aircraft Corp.

Hamm, James Douglas, B.M.E.; Jr. Research Engineer, Lockheed Aircraft Corp.

Hotson, John H., Asst. Foreman, Aircraft Div., National Steel Car Corp., Ltd., Canada.

Jongeneel, James William, M.S. in Ae.E.; Draftsman, Douglas Aircraft Co.

Lynn, Norman, Draftsman, Douglas Aircraft Co.

Macauley, Clinton Bowen Fisk, Managing Editor, *Aviation* Magazine. (See B.B. of A.A., 1942.)

McLarren, Robert, West Coast Manager and News Editor, *Model Airplane News.*

Morrill, Carle Craig, B.S. in Chem. Eng.; Installation Engineer, Pratt & Whitney Aircraft Div., United Aricraft Corp.

Post, John E. H., B. S. in M.E.; Engineer, Republic Aviation Corp.

Rinek, John Ayers, B.S. in Metall.E.; Engineering Test Pilot, Installation Dept., Pratt & Whitney Aircraft Div., United Aircraft Corp.

Roberts, Frederic Morley, B.S. in E.E.; Application Engineer, General Electric Co.

Russell, Edgar Farr, B.S. in C.E., M.A.; Instructor in Mech. Drawing, Public Schools, District of Columbia.

Sentker, Christian Lawrence, B.S. in M.E.; Aero. Engineer, Edward G. Budd Mfg. Co.

Serbin, Hyman, Ph.D.; Chief Aerodynamicist, Fairchild Aircraft Div., Fairchild Engine & Aviation Corp.

Shaw, Francis, Factory Manager, Aircraft Div., Electrol, Inc.

Necrology

George Allen Graves

Second Lieutenant George A. Graves, flying officer in the Fleet Force of the U.S. Marine Corps, was killed in action against the enemy in the Pacific area during the first two weeks of the war with Japan, December 8 to 22, 1941.

Lieutenant Graves was born in Des Moines, Iowa, February 4, 1915. A member of the Student Branch at The University of Michigan, he received the degree of B.S. in Aeronautical Engineering, became a Technical Member of the Institute upon graduation in June, 1937, and served as a Junior Draftsman at North American Aviation, Inc., in the summer of 1936. He held a commission as a Second Lieutenant in the Marine Corps Reserve and had been in active service since 1937, when he completed his Aviation Cadet training course at the Pensacola Naval Air Station.